1987

# Disposal of spent nuclear fuel and high-level waste: design and technical/economic analysis

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# Disposal of spent nuclear fuel and high-level waste: Design and technical/economic analysis

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Disposal of spent nuclear fuel and high-level waste: Design and technical/economic analysis

by

Jordi Roglans-Ribas

A Dissertation Submitted to the Graduate Faculty in Partial Fulfillment of the Requirements for the Degree of

DOCTOR OF PHILOSOPHY

Major: Nuclear Engineering

Approved:

Signature was redacted for privacy.

In Charge of Major Work

Signature was redacted for privacy.

For the Major Department

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For the Graduate College

Iowa State University
Ames, Iowa

1987

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## LIST OF ACRONYMS

AFR - Away From Reactor

a/c - Assemblies per Canister

A-E - Architect-Engineering

DD - Delay of Disposal

DOE - Department of Energy

Dr - Room-to-room Distance

DR - Discount Rate

FF - Far-Field

FHLW - Fractionated High-Level Waste

HLW - High-Level Waste

ID - Inside Diameter

ILW - Intermediate-Level Waste

KgHM - Kilogram Heavy Metal

LLW - Low-Level Waste

MRS - Monitored Retrievable Storage

MTHM - Metric Ton Heavy Metal

NF - Near-Field

NWPA - Nuclear Waste Policy Act

PWR - Pressurized Water Reactor

SF - Spent Fuel

TRU - Trans-Uranic Waste

VNF - Very-Near Field

# I. INTRODUCTION

## A. Statement of the Problem

The back end of the nuclear fuel cycle starts when the spent fuel (SF) is discharged from the nuclear reactors. The SF is composed of fertile and fissile materials, highly radioactive fission products, and structural material with lower activity. Radioactive waste is a hazardous product and must be properly dealt with. The commonly accepted method for completing the back end of the fuel cycle is the permanent isolation of the radioactive waste from the environment by burial in a deep underground repository.

Several waste forms have been proposed for disposal, most notably consolidated spent fuel assemblies and high-level waste (HLW), the fission product residue left after reprocessing the spent fuel for recovery of the fertile and fissile elements. Disposal of spent fuel (currently contemplated in the United States) is known as the once-through cycle, and disposal of HLW is referred to as the closed (or reprocessing) cycle (the choice in several European countries). An alternative closed cycle can also be used, in which the cesium and strontium, the most abundant and active fission products in the reprocessed waste, are separated from the bulk of fission products. The waste forms for disposal in this cycle are the fractionated high-level waste (FHLW) and the solidified Cs/Sr. This cycle has the purpose of introducing some beneficial changes in the repository design and providing Cs for irradiation plants, should it become in demand in the near future.

The status of the back end cycle varies depending on the country; in the U.S. a considerable backlog of SF is being stored, while in France and England, for example, the SF is being reprocessed and the HLW vitrified and kept in above-ground storage. No permanent disposal of SF or HLW has yet been performed, and there are still many uncertainties involved in the design and operation of the facilities that are part of the disposal stage. In most countries with a developed nuclear program, public opinion has become increasingly concerned about the capability of the nuclear industry for safely and economically disposing of the radioactive waste it generates. Political pressures are growing for demonstrating as soon as possible that waste isolation can be properly accomplished.

In the United States, the Department of Energy (DOE) is in charge of radioactive waste disposal and, according to the Nuclear Waste Policy Act (NWPA) of 1982, must accept spent fuel by 1998 from the utilities, which are already contributing a 1 mill/Kwh fee to the DOE's waste disposal fund. Numerous uncertainties exist today about every step involved in the waste disposal process. The currently contemplated waste disposal form is SF, but a reprocessing cycle is not ruled out. A storage method to accommodate the backlog of SF accumulated before disposal is being tested, but no final system has yet been selected. The existing designs for reprocessing cycles were made for reprocessing of short-cooled spent fuel, but under the real situation the SF available for reprocessing would have been cooled for a minimum period of 10 years. The choice of a repository location has not been made, although 3 sites (one in a salt formation, one in tuff, and the third in basalt) have been proposed by the DOE. An additional rock formation, granite, is being considered for hosting a second repository, but the issue of the second disposal site is currently being debated, and at this moment it is not known if the site selection process will continue. Still more uncertainty surrounds the detailed design of the repository facilities, although some reference designs have been completed for different scenarios and capacities. The uncertainties that exist in the steps involved in the back end of the fuel cycle must be solved in the immediate future if the nuclear industry and the DOE are to maintain credibility regarding the issue of radioactive waste management. The decision process must be performed under the mainframe of three sets of considerations, namely, safety, economics, and political constraints.

This project is concerned with one of the issues involved in the decision-making process, the economics of the back end of the fuel cycle, which is analyzed under the expected political constraints. The objective of the present work is twofold:

1. to perform a comparative economic analysis of the different alternatives for the back end of the nuclear fuel cycle, and
2. to study some issues related to the repository design, its thermal analysis in particular, and their effects on the costs of disposal.

## B. Description of the Project

The first task is the definition of the model for the back end of the nuclear fuel cycle, from the discharge of the SF from the reactor and its storage in at-reactor pools, to the final waste disposal. The model for the back end cycle is different depending on the cycle chosen. Because of the existing backlog of SF, some utilities are running out of at-reactor storage space, so that all cycles include facilities providing additional SF storage capacity. The additional capacity can be provided by so-called Away-From-Reactor storage (AFR) facilities, up to 1,900 MTHM of maximum capacity for federal facilities (limited by the NWPA) but unlimited in capacity if privately financed; or by a Monitored Retrievable Storage (MRS) facility, where the SF is consolidated and canistered. In a once-through cycle, no other facilities are involved between storage and the repository. For closed cycles, a reprocessing/solidification plant is also required. Transportation of the SF is an important part of the back end cycle and can take place in two different stages: from the reactor sites to the storage facility and from the storage facility to the disposal site. The facilities and operations involved in the back end cycle have been dimensioned in accordance with the expected scenario for the first repository. The back end cycles modeled provide a distinction between co-location of the MRS storage facility with the repository, or location away from the repository; in the latter case the Clinch River site in Tennessee is assumed, following the DOE's application. The models and the applicable scenarios are presented in Chapter III, along with a brief description of the facilities required and the basic operations performed in them.

The design of the underground facilities in the repository depends upon the densities of waste disposal that are achieved. The waste forms to be emplaced in the repository are heat-producing and there are certain thermal limits that can not be exceeded in order to maintain the integrity of the waste forms and the repository. The densities of disposal are determined by the maximum permissible thermal loadings to avoid violation of the thermal limits. These thermal loadings depend on a number of parameters, among which the waste form and age at disposal are the most important. A parametric thermal analysis of the repository has been performed in order to determine the maximum permissible thermal loadings in different repository locations and for the three cycles considered. The effect of several important parameters on the thermal loadings has also been determined. In performing the thermal analysis, simplified heat transfer models for emplacement in a repository have been developed. The details and results of the thermal analysis are presented in Chapter IV, while a description and development of the thermal models is included in Appendices A and B.

The next item is the development of the economic model, which is described in Chapter V. The economic model has been designed for calculation of the costs of transportation and storage of spent fuel, and waste disposal. The cost evaluation is based in the capacities and lifetimes defined in the scenarios for the first repository. Several sets of inputs are used by the economic model, namely the dimensional design of the repository, the flow of waste per year in all facilities involved, the results from the thermal analysis concerning the maximum permissible thermal loadings, and a set of unit costs of facility capital and operations. The economic model is parametric, and both unit costs and dimensional parameters can be changed in the input for determining the sensitivity of the model to variations in different parameters, or to obtain better cost estimates as new information becomes available concerning design aspects or cost issues. A set of unit costs from existing publications were used as a baseline input, and an uncertainty band was associated with the baseline case. Details on the unit costs for the various facilities and operations are given in Appendix C.

The possibility of minimizing the total cost by delaying the start of disposal operations has been taken into account in the development of the economic model. Because of the heat generation in the waste, aging before disposal can result in a reduction of the required disposal area in the repository, for the heat source is decaying. The delay of disposal can produce two cost reductions, one in decreasing the excavation costs and the other in deferring the disposal costs. On the other hand, delaying the disposal causes the storage costs to increase, and the existence of a least-cost situation depends on the relative amount of storage cost increase and disposal cost reduction. The economic model optionally searches for the existence of a least-cost situation. This optimization has been made optional, given the likelihood of political and social pressures to avoid deferral of waste disposal.

The economic model has been applied to a number of situations, with the main objectives being the comparison of the different cycles, the possible rock formations for hosting a repository, and the location of the storage facility with respect to the disposal site. The sensitivity of the model to variations of different parameters has also been analyzed, for the different host rocks and fuel cycles. The numerical results are presented in Chapter VI, where ranges of costs associated with the baseline are given. A qualitative discussion of the costs obtained is included, and it is particularly oriented to the comparison of repository host rocks and fuel cycles. Some important issues related to the repository design and to the SF transportation are also analyzed in Chapter VI, to determine the impact they may have on the final waste management cost.

The conclusions from the present work are given in Chapter VII. A summary and brief discussion of the most significant results obtained in both the thermal and economic analyses are presented. Based on the results found concerning the effect of different parameters on the outcome of the economic model, a set of recommendations for future work is included in that chapter. In particular, several research projects that could result in significant cost reductions are suggested.

The thermal and economic models and the results obtained with them depend upon the quality of the input information used. The thermal limits might be determined to be different than those used and then the results of the thermal analysis might change in value; or the model for the back end cycle might change; or the unit costs might change substantially. These all could change baseline costs significantly. Nevertheless, the qualitative results, especially those concerning the comparison of repository host rocks, back end cycles, and facility locations, should still be valid. Indeed, both models could be used for studying the effect of introducing design or cost changes, and for comparison of different hypotheses or situations.

## II. LITERATURE REVIEW

The commercial nuclear power industry has been operating since the late 1950s. Spent fuel has since then been generated by operating nuclear power plants. The spent fuel contains hazardous radioactive materials that must be isolated from the human environment. A permanent solution for radioactive waste management and isolation must be found by the nuclear industry to achieve full credibility and public acceptance (1).

The management of the SF from the time it is discharged from the reactor until the hazardous waste has been properly disposed of forms the back end of the nuclear fuel cycle. Two different options have normally been proposed for the back end of the fuel cycle; the once-through cycle and the closed (recycle or reprocessing) cycle (2). The choice between the two cycles depends upon the supply of fresh fuel, the demand for recovered products in reprocessing, the type of reactors used and the economics of the entire fuel cycle. Some countries are currently basing their back end cycle on a closed cycle, such as France, Japan, and the United Kingdom (3,4), under arguments based on economic grounds (5). An additional cycle has been proposed, which consists in fractionating the cesium and strontium from the reprocessed waste and solidifying the FHLW and Cs/Sr separately for later disposal (6,7).

The once-through cycle is currently being considered in the United States, but a closed cycle has not been ruled out, its selection depending essentially on economics (8). Commercial reprocessing was briefly performed at the West Valley facility, New York, and a large-scale (1,500 MTHM/year) plant was built in Barnwell, South Carolina (3), but never started up, first because of political (nonproliferation) reasons, and later because of economics.

The U.S. Department of Energy is committed to completing the back end of the nuclear fuel cycle, as mandated by the NWPA of 1982. The NWPA specifies the political procedure for selection of a disposal site and, more important for the purpose of this project, sets an original deadline for starting disposal operations (9). The DOE prepared a Mission Plan (9) scheduling the operations and procedures in accordance with the NWPA that had to be accomplished up to the opening of the first repository. However, some delays have already occurred with respect to the initial Mission Plan and the DOE has recently applied for approval of a revised set of schedules. The original plan targeted the operations of the first repository by the year 1998, and the revision calls for a delay until the year 2003. At the same time, an application for building an MRS storage facility has been filed to store the SF from 1998 to 2003 and prepare it for disposal (10).

Adequate technology is currently available for the proper disposal of radioactive waste, whether reprocessed or not, and the different facilities and operations involved in the back end of the fuel cycle have been designed or, in some cases, carried out (11,12). Although final designs for all facilities are not complete, reference designs exist, and extensive research has been performed concerning particular aspects of waste management.

SF has been stored for many years, normally wet storage in at-reactor pools (13), and is a well-known process. Many storage methods have been proposed, and dry storage systems are preferred for an MRS facility. The DOE determined after a comparative analysis that the best choices for SF storage were the dry cask and the drywell methods (14). Detailed designs for both methods were completed (15) and the dry cask method was finally selected (16), with the drywell considered as a feasible alternative. A program for testing different dry casks is currently under way (17).

For the closed cycles, reprocessing is also a known technology, and considerable experience has been gained in the reference Purex process (3), in both pilot and large-scale reprocessing plants in the U.S., France, Japan, U.K., West Germany and India (3,18,19). Because long-cooled spent fuel would be available for reprocessing in the U.S., a modified reprocessing plant is currently being re-designed for this type of fuel at Iowa State University (20). Solidification of liquid HLW from reprocessing has also been the object of extensive study. The preferred method is the vitrification of the waste oxides into a borosilicate matrix, although a number of waste forms and glass compositions have been proposed (21-23). HLW glass characteristics for different glass forms have been investigated and compared (24,25). The only country performing commercial vitrification of radioactive waste into a borosilicate glass matrix is France, and considerable experience has already been gained (26,27). The process for fractionating the Cs/Sr from the bulk of the HLW has been developed, and solid waste forms for isolation of these two elements have been investigated (7,28-30). A further optional operation that can be performed after reprocessing, the recovery of valuable noble metals that are found among the fission products, has been described (31), and a recovery plant design and feasibility study was recently performed at Iowa State University (32).

The underground disposal of radioactive waste has generated a considerable amount of literature, for many aspects must be considered and many operations designed and evaluated. The overall feasibility and environmental impact of underground disposal was one of the first questions to be answered, and a series of projects were undertaken to provide a general assessment of technology and risk involved in underground disposal (33-37). A few pilot repositories, often using simulated waste canisters have also been built for in-situ data collection in several rock formations and performance of heat transfer experiments (38-40).

Many aspects related to the disposal operations have been studied in detail. They cover a wide range of issues, such as mining techniques (41), underground repository design (42,43), stability of the disposal rooms (44), chemical interactions, and others. Two particular items have deserved special attention: the first concerning the ability of the geologic media to function as a waste isolation system effectively, by avoiding the release of radionuclides to the environment (45); and the second referring to the interaction between waste form and medium, which covers such aspects as geochemical interactions and thermomechanical effects of waste emplacement (46-50). Linked to the thermal considerations and the effectiveness of the isolation barriers is the program for development of canisters and overpacks for the waste form to be disposed (51-55), which has resulted in a variety of proposed materials and dimensions, with the most conservative design including a Ti overpack. Reference designs for a repository have also been completed, under different assumptions for scenarios, host rocks, and underground design (56-59).

Transportation of SF is a known operation, since it has been done for a number of years, and experience has been gained. Studies for estimating transportation requirements for a first disposal site have been completed, and they include logistics, risk assessments, and modeling depending on repository location (33,60,61).

Because the operations involved in the back end of the nuclear fuel cycle have a high associated cost, the economics of the back end cycle has been the object of thorough investigation. Some authors have estimated costs involved in all the waste management operations, under assumed scenarios (62,63), but most of the economic analyses have been applied to one particular component of the total waste management cost. Spent fuel storage costs have been widely studied, since they are the first costs incurred in the back end of the cycle. Cost analyses comparing different storage methods, both wet and dry, exist (14,64,65), and more recently, cost estimates of the two preferred storage systems, cask and drywell storage, have been obtained (66,67). The disposal stage has been analyzed from the economic point of view in different projects. The disposal costs for two early repository designs in salt were summarized and compared in a reconciliation study (68), and later standardized for application to other repository locations (69). Other economic studies of disposal operations under different scenarios and geologic formations have been completed, with relatively poor agreement among them (70-75). The repository economics study performed by Forster (71) is particularly interesting, because a variety of scenarios are compared and a sensitivity analysis is presented. Cost estimates of unit operations to be carried out in the repository have been calculated, such as for waste emplacement (76), waste packaging (54,55), and shaft construction and unit mining costs (59). The impact of different parameters on the cost of disposal has been analyzed in some instances: effect of canister length (77), of the thermal limits (78), and the influence of Trans-Uranic waste (TRU) emplacement in the repository (79). SF transportation cost estimates also exist for different situations, such as truck or rail shipping, different repository locations, and for various cask designs (33,63,66,80,81).

Computer models have been developed to estimate the cost of disposal operations; a simplified model was created by Henry (82), and a more recent model was prepared by Clark et al. (83). Clark's model, called RECON, includes many details and the disposal costs are divided into many items, requiring the user to supply a very complete set of data when running the program, making the application to generic studies rather difficult. The effect of locating the MRS facility away from the repository site or co-locating both facilities has also been the object of an economic analysis (84) which indicated that co-location of the MRS with the repository results in lower system costs. The cost of consolidating the SF before disposal or before transportation, for volume reduction, operation that was not included in early designs, has been recently estimated (54,55,84).

In the waste disposal technology assessment published by the DOE (33), it was pointed out that delaying the disposal operations could decrease the waste disposal costs. Becker and Varadarajan (85) have made a semianalytical model formulation of the waste aging problem, pointing out the convenience of delaying disposal if the resulting storage cost increase is smaller than the decrease in disposal costs. Later analyses have been performed with the inclusion of the possibility of finding a least-cost situation by delaying diposal (86,87,88).

The present study uses information from the existing designs of the facilities and operations involved in the back end of the fuel cycle and the expected scenario for the first repository (10,88). The information is used in developing and dimensioning a model of the back end of the nuclear fuel cycle. An economic model is then developed for estimating transportation, storage and disposal costs in different rocks. The model is parametric and the sensitivity to different parameters is analyzed. The parameters that in some cases have been studied separately are all incorporated in the economic model, and an option for optimizing the system costs by aging the waste before disposal is also included. Finally, the difference between the three different back end cycles are analyzed, and the possibility of lower disposal costs for a closed cycled with respect to a once-through cycle, as suggested in a preliminary study (89), is investigated.

# III. THE BACK END OF THE NUCLEAR FUEL CYCLE

## A. Introduction

This chapter describes the different models for the back end of the nuclear fuel cycle that are compared in the economic analysis. This introductory section covers a general overview of each of the three cycles. A brief description of the facilities and operations involved in each of the back end cycles is presented in Section B, where the features directly affecting the economic analysis are particularly outlined. Detailed descriptions and designs for all the facilities have been published (33,56-58,66) and parameters that can affect the total system costs have been identified and analyzed in some studies (71,77-79,85-87). Concluding the present chapter, Section C describes the baseline scenario considered in the economic analysis as well as the most significant alternatives studied.

The spent fuel discharged from a thermal nuclear reactor contains most of the U-238 that was originally loaded with the fresh fuel, about 3 w/o (depending on burnup history of the fuel) of highly radioactive fission products and actinides, among which there are significant amounts of fissile materials such as U-235 and Pu-239. When the spent fuel assemblies are removed from the reactor, the heat generation is very high (of the order of 30 Kw after 1 month) and cooling is required (3). At-reactor storage and cooling in water-filled pools is common practice.

The current policy in the United States regarding the back end of the nuclear fuel cycle is to permanently dispose of the spent fuel after consolidation of the assemblies for volume reduction. This is known as the once-through cycle (2). The block diagram for this option is shown in Figure 1. To provide backup storage for the utilities running out of space in the at-reactor pools, the NWPA authorized a maximum storage of 1,900 MTHM in Away-From-Reactor (AFR) facilities (9), although some power plants are considering an increase in the at-reactor storage capacity, mainly by the use of dry storage casks (17,67). The MRS, a facility that is not contemplated in the NWPA and thus, has no limit in its storage capacity, is intended by the DOE to operate as a facility for waste preparation for disposal (consolidation and encapsulation of the SF). However, because of the delay in the repository schedule it is currently thought that most (or all) of the spent fuel will be stored for some period of time in the MRS after the DOE takes title to the SF from utilities, starting in 1998 (10).

An alternative to the once-through cycle for LWR reactor fuels is the closed or reprocessing cycle. In this option the spent fuel is reprocessed in order to recover the valuable fertile and fissile material contained in it. The actinides recovered during this process can be incorporated into new fuel for further use in fast reactors or in thermal (mixed-oxide fuel) reactors. Several countries with developed commercial nuclear programs, most notably France, the United Kingdom, Japan, and the Federal Republic of Germany, have chosen the reprocessing option (3,4). Commercial reprocessing is not currently

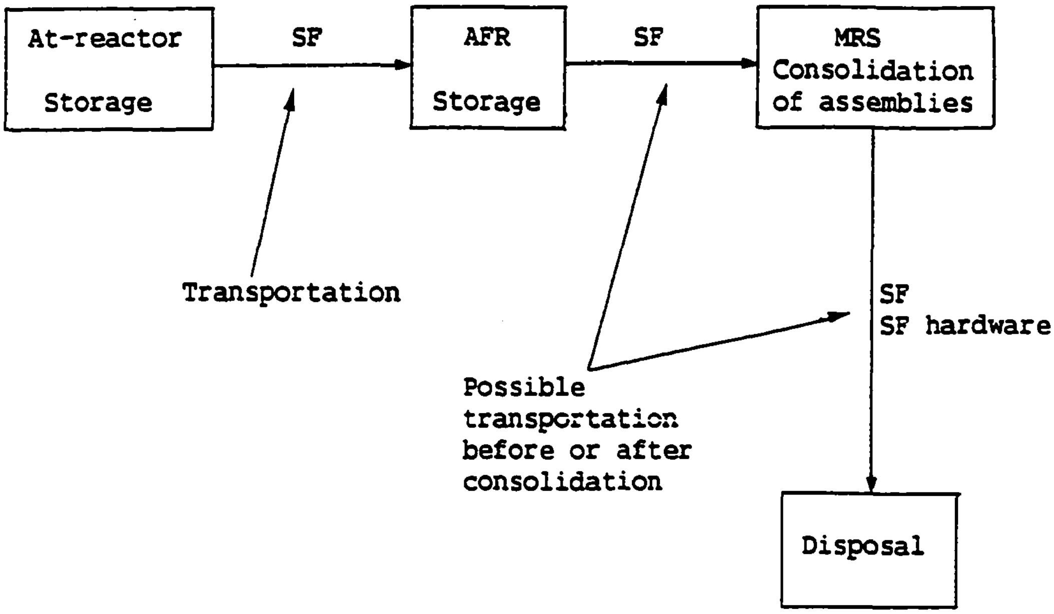


FIGURE 1. Block diagram of the once-through back end cycle

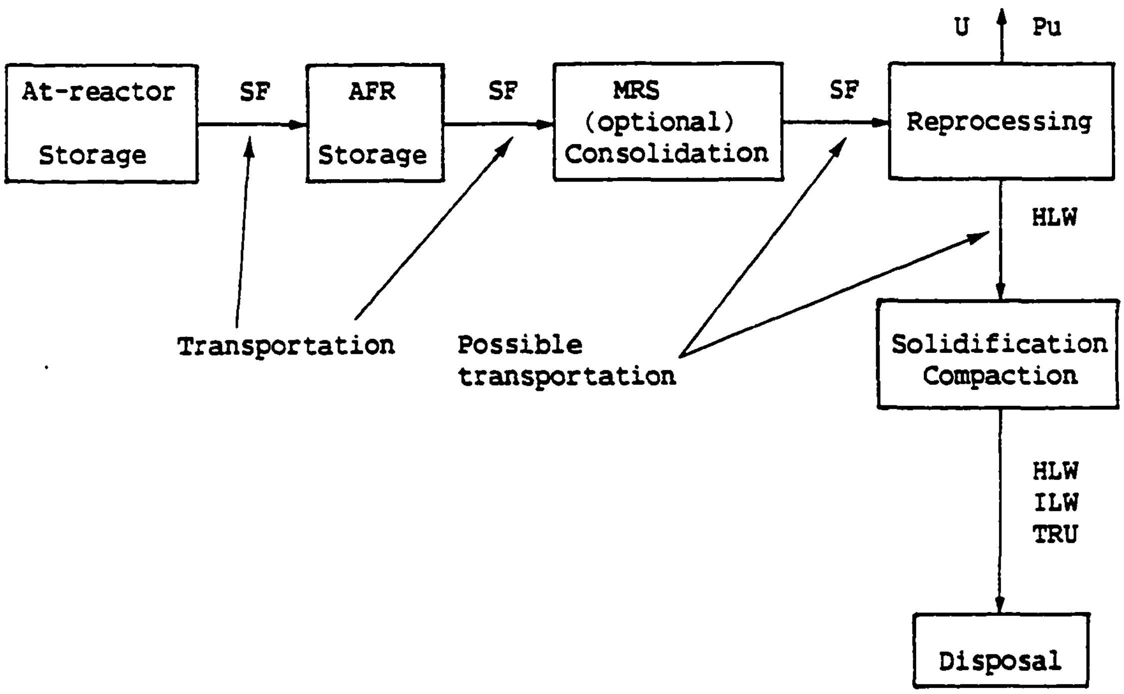


FIGURE 2. Block diagram of the reprocessing back end cycle

contemplated in the United States, although it was performed briefly (West Valley reprocessing facility, New York) and a large plant was built (Barnwell, South Carolina) but never started up (3). The closed cycle however, can still be a viable alternative in this country, for it would not result in waste of a large energy resource and at the same time could lead to reduction in disposal costs with respect to the SF disposal option. In addition, disposal of reprocessed waste might result in a total lower risk to the population than disposal of spent fuel, although this can only be asserted after a thorough comparative risk analysis of the two cycles.

The closed cycle, which is shown in Figure 2, includes more operations than the once-through cycle. An AFR facility to provide buffer spent fuel storage before reprocessing would also be necessary given the existing backlog of spent fuel (90). Since it is unlikely that a reprocessing plant could be started up before the DOE takes title to the SF from the utilities, an MRS would probably exist in a closed cycle as well, and if not co-located with the repository, consolidation could still take place to ease storage and transportation requirements. After the uranium and plutonium are extracted in the reprocessing stage the remaining products form the so-called high level waste (HLW), which is in the form of a liquid solution of fission product nuclides in nitric acid. Small amounts of actinide oxides still remain in the waste stream. The high level liquid waste, highly radioactive and heat producing, must be transformed into a proper form for disposal. The commonly accepted process consists of removing the nitric acid and solidifying the liquid waste into a borosilicate glass matrix. Other waste types are also generated during reprocessing, such as the TRU (trans-uranic) low activity $\alpha$-contaminated waste, and intermediate level waste made up of SF hardware and cladding hulls. The cladding hulls and SF hardware are canistered after compaction and the TRU waste is incinerated and incorporated into a cement matrix before disposal (79).

A variation of the closed cycle consisting of a process to fractionate the Cs and Sr contained in the HLW has also been proposed (7,28). These two fission products account for most of the heat generated in the HLW (about 85 % at 10 years). Cesium and strontium can be extracted during the reprocessing operations and solidified separately from the bulk of the HLW. In the present study this cycle is referred to as the FHLW (Fractionated High-Level Waste) cycle. The fractionated and vitrified high-level waste would be disposed after reprocessing as in the regular closed cycle, while the Sr and part of the Cs could be stored above-ground. The remaining Cs could be used in irradiation facilities. After a certain period of storage the Cs and Sr would be disposed in the same repository.

The principal advantage of this scheme is that the waste at disposal has a lower heat generation rate, thus requiring a smaller disposal surface area. This reduction in the required disposal area would open the possibility of using the same repository for a longer time, which might lead to a net decrease in the disposal costs. The flow diagram of the FHLW cycle is shown in Figure 3. Other than the variations in the reprocessing flow chart and the new Cs/Sr waste line, the rest of the cycle resembles the reference closed cycle.

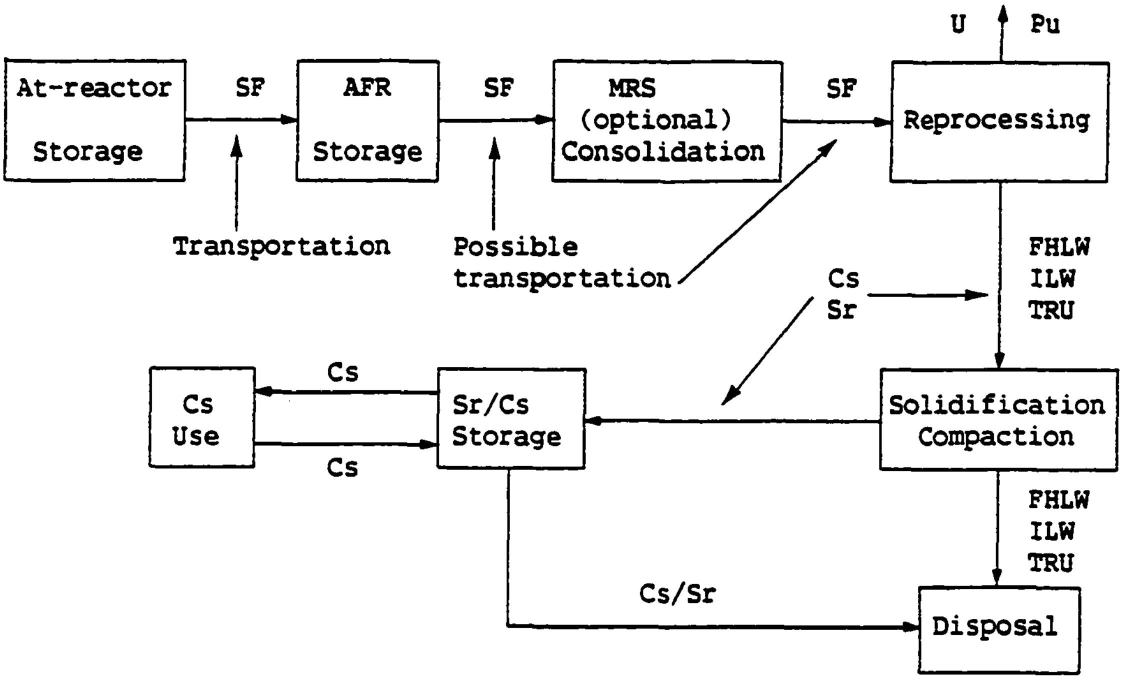


FIGURE 3. Block diagram of the Fractionated High-Level Waste cycle

B. Description of Facilities and Operations

Although the first operation performed after the spent fuel is discharged from the reactor is the at-reactor pool storage, this will not be considered in the economic analysis, since each utility is responsible for the costs incurred in this stage. According to the Nuclear Waste Policy Act of 1982 (NWPA), the United States Department of Energy (DOE) has the responsibility to properly store and dispose of the spent fuel (or HLW if a closed cycle were chosen) delivered by the utilities (9). A fee of 1 mill/Kwh is paid by the utilities operating nuclear power plants to the DOE to cover the disposal charges (91). Transportation charges from the power plants to the DOE receiving plant, the MRS facility, are also costed by the utilities. These transportation charges, however, have been included in the present analysis in order to study the impact of transportation in the total system costs. A second transportation cost would be incurred if the MRS facility is not co-located with the repository. In that case, the DOE would be responsible for these charges, since they would occur after the DOE has taken title to the spent fuel.

1. Transportation of spent fuel

Transportation of SF can be done by truck or rail. Radiation shielding and cooling are required because of the high radioactivity levels of the spent fuel, and this results in big and heavy transportation casks. Truck shipments can only manage casks with capacities for 1 or 2 PWR fuel assemblies (unconsolidated). In order to minimize the number of shipments required, rail transportation is preferred, for rail casks can be bigger and have a larger capacity, of 7 PWR fuel assemblies or more. For the purpose of this study it is assumed that 100 % of the shipments are done by rail, which is likely to be the case for the transportation stage from the MRS to the repository, when this is necessary.

Several rail cask designs exist, and the common reference casks are the NLI 10/24 (capacity for 10 PWR assemblies), manufactured by

National Lead Industries, and the IF-300 (capacity for 7 PWR assemblies), manufactured by General Electric (33,63). Because National Lead Industries is no longer in the spent fuel transportation business, the IF-300 cask is used as the reference in this study. The IF-300 is designed for a maximum heat removal of 76 Kw with installed air blowers operating, or 62 Kw without the blowers in operation (33). In calculating the number of shipments required, the rated capacity of 7 PWR assemblies (3.227 MTHM) is used for unconsolidated spent fuel transportation. However, in some of the scenarios considered, transportation of consolidated assemblies would take place from the MRS to the disposal site, and the capacity used in that case is 9.68 MTHM. An average volume reduction by a factor of 3 during consolidation has been assumed, and it is also assumed that the inner shelves of the IF-300 cask could be easily modified to accept canisters of consolidated fuel rods instead of unconsolidated assemblies. The maximum heat removal capacity of the cask would not be exceeded by the loading of 9.68 MTHM, whose maximum heat generation rate would be 11 Kw for 10-year old spent fuel.

## 2. Monitored Retrievable Storage Facility

The DOE is planning to build a Monitored Retrievable Storage (MRS) facility, where the SF would be prepared for disposal, through consolidation and encapsulation. The proposed location of this facility is in the State of Tennessee, at the site of the ill-fated Clinch River reactor. The DOE must fulfill the statement of the NWPA and accept SF from the utilities starting in 1998, but because of the repository delays, the DOE will have to store for a number of years the SF received, and is planning to do so in the MRS. Unlike the AFR facilities, the storage capacity of the MRS is not limited by the NWPA, but the DOE wants to voluntarily restrict the maximum storage capacity of the MRS to 15,000 MTHM, to quiet fears in the State of Tennessee that the MRS will become a permanent disposal site (92).

Most of the operating nuclear reactors in the U.S. are located east of the Mississippi river, and an MRS facility in Tennessee would result in relatively low spent fuel transportation costs from the power plants to the MRS. The prospective sites for a repository, however, are all in the western states, far from the MRS facility, resulting in high transportation charges from the MRS to the disposal site. Co-location of the MRS facility with the repository may result in lower total (utility plus DOE) transportation charges. At the same time, some redundancy in facilities would be avoided by co-location, namely the waste receiving/handling facility of the disposal site complex could be used for the MRS facility as well (84). For these reasons, the two possible locations for the MRS facility are considered in the economic analysis.

The MRS facility consists of a waste receiving and handling building and the storage field. The waste receiving building has capabilities for inspecting, treating and re-encapsulating the spent fuel in case of necessity. Inspection is performed upon arrival and before shipment (if any) to the repository. The storage field is the part of the facility where the spent fuel is placed for storage.

The DOE, as a result of a comparative study among different storage methods (dry and wet) recommended further study of two of the options analyzed (14), the dry storage cask and the drywell storage methods. The dry cask method is normally taken as the reference storage system. The cost of the cask and drywell methods are similar, but less surface area is required for the storage field in the dry cask system.

Dry cask storage systems have been designed, consisting of a set of containers holding a number of spent fuel assemblies and placed outdoors on a concrete pad. The casks provide shielding and cooling for the spent fuel. The reference cask is the REA-2023, a metal cask with a capacity for 24 unconsolidated PWR fuel assemblies (11 MTHM). The REA cask, already tested by DOE, is unlikely to be selected for the MRS, since the manufacturer went out of business (17), but similar designs already exist (Westinghouse's MC-10, Transnuclear's TN-24P). The REA cask is taken as the reference here because cost estimates exist for this design. The cost of the casks is considerable and a reduction in the number of casks required would result in a significant cost reduction. For this reason the possibility of storing spent fuel after consolidation is analyzed.

The maximum heat removal capacity of the REA-2023 design is 47 Kw (66). Assuming again a reduction by 3 in volume by consolidation, a total of 33 MTHM could be stored in 1 cask. For 10-year old spent fuel this amount would result in a heat generation of about 35 Kw, well below the maximum rating.

Operations in the storage field consist of emplacement and retrieval of the storage casks, to be performed with a transporter/crane, and surveillance operations on the loaded casks. The surveillance operations must monitor the temperature and the radioactivity levels in each storage cask to detect possible leakages or overheating. The design of the storage cask already accounts for the surveillance requirements.

3. Reprocessing and solidification

These processes only take place in the closed cycles. The cost estimates for reprocessing and vitrification of the HLW are not included in the economic model. Current cost estimates for these facilities are based on designs for reprocessing of short-cooled spent fuel (150 days to 1 year after the discharge from the reactor). However, the spent fuel that would be available in the United States for reprocessing is already much older than 1 year, thus giving the possibility of some cost reduction in reprocessing and vitrification due to the decrease in radioactivity levels and heat generation rates. A re-design of the reprocessing facilities to handle long-cooled spent fuel is currently being done at Iowa State University (20). Although the reprocessing plant costs are not included in the model, the issues related to this facility that are linked to the rest of the economic analysis, such as facility location and waste forms, are briefly discussed here.

A full size commercial reprocessing plant was built in Barnwell, South Carolina, but it has never been started up. This plant is currently being dismantled. Therefore, the possibility of locating the reprocessing plant in S.C. is ruled out in this study, and only one possible location for the reprocessing/vitrification facilities is considered, this being the disposal site, with the purpose of minimizing transportation requirements.

It is assumed that the SF is reprocessed using the Purex process, which has become the standard method for LWR fuels (3). In this process the spent fuel is chopped and dissolved in nitric acid. The U and Pu are then recovered by solvent extraction with Tri-Butyl Phosphate (TBP). The waste stream after the extraction is in the form of a solution of fission product oxides in nitric acid. In the regular closed cycle the waste stream is vitrified after evaporating the nitric acid. The reference waste form is a borosilicate glass containing dissolved F.P. oxides. In order to check the effect of the glass canister size and the waste oxides concentration on the economics of the back end of the fuel cycle, 3 different canister diameters will be considered, 30, 40 and 50 cms, each with 3 possible waste concentrations, 10, 15 and 20 w/o. The reference canister height is assumed to be 1.2 m, so that 3 canisters would be dimensionally equivalent to one canister of SF. Because of the flexibility in choosing the canister length, the short HLW canister would be preferred in order to ease the emplacement and handling operations in the repository.

Other waste forms generated during reprocessing are the $\alpha$-contaminated and the SF hardware/hulls wastes. After volume reduction, the amounts of these wastes that would be generated are (66,79):

- TRU-waste: One 55-gallon drum per 1 MTHM.
- Cladding Hulls: One canister (0.66 x 4 m) per 5.9 MTHM.
- Spent Fuel Hardware: One canister (0.66 x 4 m) per 11 MTHM.

For consistency with the dimensions of the HLW canisters, it is assumed that 5.9 MTHM will generate 3 canisters (0.66 x 1.3 m) of hulls waste and 11 MTHM will generate 3 canisters (0.66 x 1.3 m) of hardware waste. The waste canisters are assumed to be inspected before leaving the reprocessing/solidification plant. The only operation left before disposal is the installation of an overpack, except for the TRU waste drums, which are ready for disposal.

In the fractionation cycle, reprocessing is performed as described and the Cs/Sr are extracted from the HLW stream before vitrification. The fractionated HLW and the Cs/Sr are then vitrified separately. A design for this process has been performed (7). A canister diameter of 32 cm is assumed in this study for the Cs/Sr waste form. With a production of Cs/Sr solidified product between 1.7 and 2 $ft^3$/MTHM, three canisters of 0.32 x 1.2 m would hold the Cs/Sr of approximately 5 MTHM. The fractionated Cs could be rented for irradiation plants since reprocessing is the only important source of Cs-137, one of the preferred isotopes for food irradiation facilities. The rental fees of the irradiation sources could represent a significant income for the reprocessing plant.

The same characteristics and volumes of TRU and intermediate-level wastes described for the regular closed cycle are applied to the fractionation cycle. After removal of Cs/Sr, however, the FHLW has a much lower heat output than in the regular closed cycle. The same canister sizes and waste concentrations are assumed for the fractionation cycle, but because Cs/Sr account for about 11 w/o of the original HLW, a reduction of 11 % in the number of canisters of FHLW in the fractionated cycle with respect to the HLW cycle is assumed.

A further consideration about reprocessing is the possibility of recovering scarce noble metals that are found among the fission products in significant quantities. The recovery of such noble metals as Ru, Rh and Pd can be performed right before vitrification of the main waste stream in both closed cycles. An analysis of the strategic importance of these metals, the recovery methods and economic considerations has been performed at Iowa State University (32). Selling the noble metals would represent an additional source of revenues for the operators of the reprocessing plant.

### 4. Disposal

The NWPA of 1982 stated that a number of prospective repository sites had to be identified and proposed to Congress by the DOE. After the initial proposal, 3 sites would be chosen for exploration and characterization. One of the 3 sites will become the location for the first repository. The initial schedule for starting operations of the repository was the year 1998, according to the NWPA and the subsequent DOE Mission Plan. However, some delays have already ocurred with respect to the original Mission Plan, and the DOE is expected to present at the end of May of 1987 an ammendment to the Mission Plan that calls for a 5-year delay to start repository construction and operations (10).

The three tentative sites have already been identified by the DOE and construction of an exploratory shaft in each of them is due to start in the very near future. The three proposed locations for the first repository are Hanford, WA (a basalt formation in the Columbia Plateau), Yucca Mountain, NV (tuffaceous formations), and Deaf Smith Co., TX (bedded salt formation) (93). Plans for a second repository are more uncertain, but it is likely to be built in a granite formation in the eastern half of the U.S. The economic analysis is applied to the four rock formations, and particular data for the identified locations are used whenever possible, with the exception of granite, for which generic characteristics are assumed.

Different repository designs have been performed, covering a range of dimensions, capacities, and concepts (33,66,56-58). A disposal site is divided essentially into two sets of installations: the above-ground facilities and the underground mine, the repository itself, connected by a number of shafts. The dimensioning of the facilities as used in the economic model has been done using data from existing repository designs, and adapting it to the requirements of the scenarios presented in Section C of this chapter.

The above-ground facilities consist of the installations necessary for waste and rock handling, and all the auxilliary operations. The waste handling building includes the receiving and treatment facilities, which could be used for the MRS facility should it be co-located with the repository. A waste packaging plant constitutes the second part of the waste handling installations. In this facility an overpack is mounted around the canisters before the waste canisters are transferred to the underground mine for disposal. Ventilation structures for air supply to the mine development and disposal areas are another major component of the above-ground buildings, along with the rock handling facilities, rock storage fields and rock transfer equipment. An administration building hosts the administrative tasks, the technical management, monitoring and laboratory services, safety and security headquarters, and a cafeteria. Auxilliary buildings for sewage treatment, water supply, utilities and emergency power, firehouse, maintenance and warehouse, visitor's center, and security gatehouses complete the set of surface facilities. Note that in the case of the closed cycles, the reprocessing and solidification plant would be also part of the surface installations.

Shafts including the headframes and hoisting equipment are built to connect the surface facilities with the underground mine. A total of four shafts are assumed for a SF repository, one for men and materials, one for waste, and two for ventilation, air intake and exhaust. An additional shaft for reprocessed waste disposal is normally included in the existing designs, to handle the low and intermediate waste transfer operations. In the present work the diameter of the shafts are assumed to be (59):

- Men and material shaft - 8 m
- Waste shaft - 4 m
- Air intake shaft - 7 m
- Air exhaust shaft - 7 m
- LLW/ILW shaft - 3 m

The depth of the underground facilities depends on the disposal site. The repository in basalt would probably be built at a depth of about 1000 m (94); the repository in salt is contemplated at a depth of 750 m (95); and for tuff there are two options being studied, 350 and 700 m, which corresponds to a repository above and below the water table, respectively (96,97). Since no location has been identified for a repository in granite, a depth of 750 m is assumed in the present work.

The underground facility consists of a central hall shaft area where the shafts end, the mining and emplacement equipment is assembled and materials required for the underground operations are stored. The rest of the underground area is made up of disposal panels, sets of disposal rooms framed by access and ventilation corridors. The disposal rooms are excavated using the room-and-pillar method. One row of boreholes is drilled in the floor of each room and the overpacked waste canisters are emplaced inside them, at a rate of 3 HLW or FHLW canisters, or 1 SF canister per borehole. A metal sleeve and a bentonite buffer is also emplaced surrounding the overpack. The bentonite buffer has the purpose of acting as a sealing ion exchange medium and also delays the transport of radionuclides out of the borehole should the waste form be contacted and dissolved by groundwater if the overpack and canister fail. An optional air gap of 6 cm (see Appendix A) can be considered between overpack and sleeve for easing the emplacement and possible retrieval operations. Emplacement of the waste in horizontal boreholes has been considered in some repository generic designs, but emplacement equipment and operations would be more complicated with this method. Following the more usual designs only vertical emplacement is considered here.

The disposal rooms are assumed to be 3 m wide. With borehole diameters around 1 m, a room width of 3 m provides a 1 m clearance at each side of the drilled hole, which should be sufficient for drilling and emplacement operations. The height of the rooms is assumed to be 3 m (3.5 in salt, because of salt creep) for HLW/FHLW disposal and 5 m (5.5 in salt) for SF disposal, which would again provide over 1 m of clearance in each case, given the height of the canisters to be disposed. The reference length of the disposal rooms is 50 m and its effect in the system cost is analyzed in the economic model. A relatively short room would not require as much roof support as a very long room, and at the same time would add more flexibility to the mining operations by providing more mining faces.

A waste retrievability period will very likely be required by regulations concerning the repository. In the present model a reference period for retrieval of 5 years is assumed, although the possibility of a 25-year period is currently being contemplated. The longer the retrievability period (delay of room backfilling) the more expensive the repository is likely to be, since the repository would be in operation for a longer time and additional roof support might be required. At 25 years the temperature rise in the rooms and pillars between the disposal rooms becomes significant and more stresses are created. A drawing of the repository lay-out is shown in Figure 4.

Several issues concerning the repository design deserve especial attention and are briefly discussed below. Because the waste forms to be emplaced in the boreholes are heat generating, the distance between boreholes (canister pitch) depends on the maximum density of disposal (watts per unit surface area) that can be achieved without violating certain limits. In some conceptual repository designs a constant disposal density has been used, regardless of canister sizes or other parameters that are likely to affect the thermal loading. The approach used in the present design has been to determine the maximum acceptable thermal loadings as a function of a set of parameters, age of the waste at disposal and canister size in particular. In the economic model a "safety factor" is then applied to the maximum allowable thermal loading to determine the design thermal loading (33). The development of the thermal analysis is explained in detail in Chapter IV. In the thermal analysis a set of constraints related to maximum temperature limits for waste form, canister and host rock were used to determine the maximum allowable thermal loadings. The thermal loadings so obtained were compared with the maximum thermal loadings acceptable

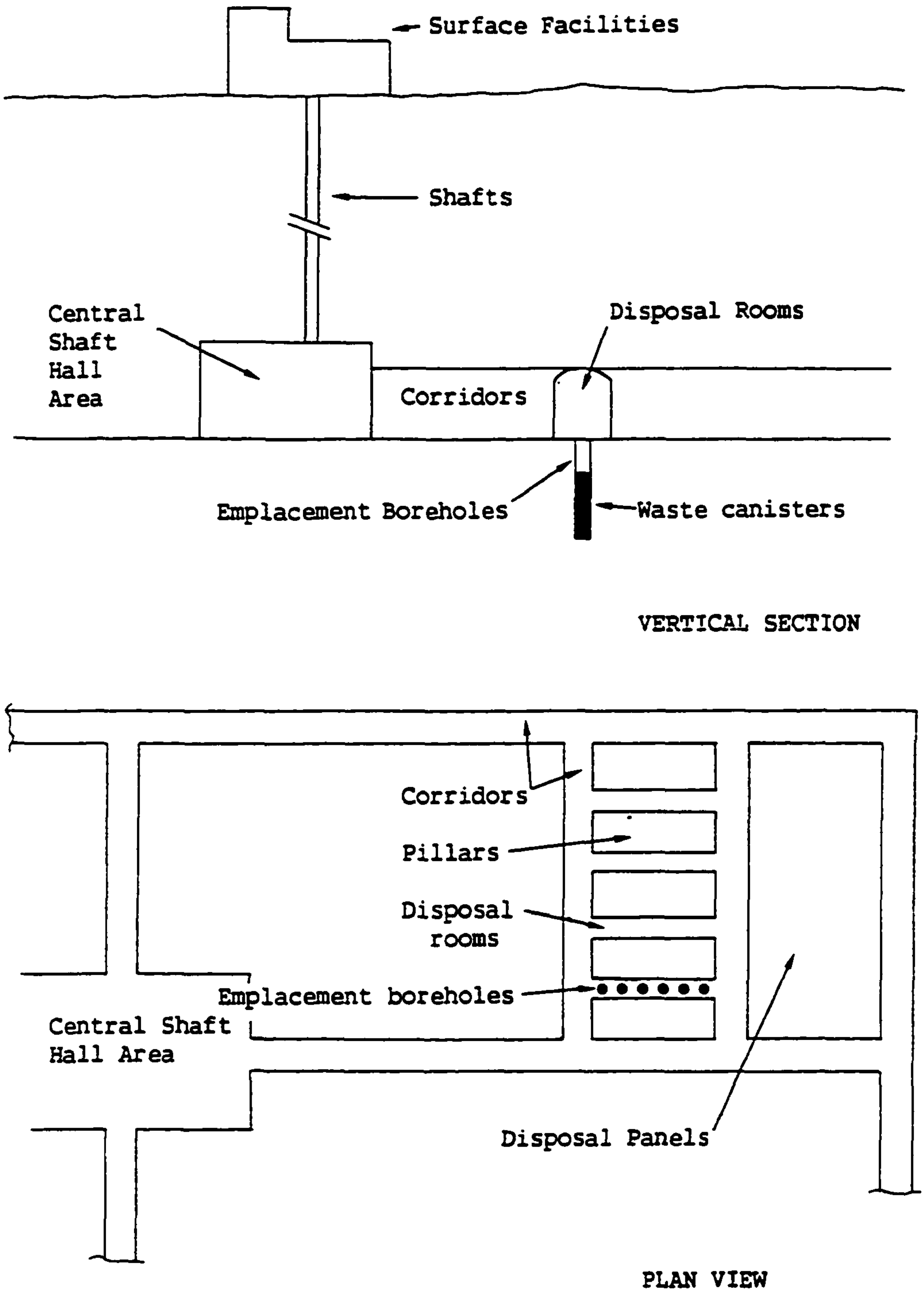


FIGURE 4. Conceptual repository lay-out

from the mechanical (room and pillar stability) point of view (48), and they were within the limits. The possibility of an additional constraint, quite uncertain, has been contemplated in some recent designs. The rate of release of radionuclides from the repository to the surface by water transport is likely to be limited by regulations under assumed scenarios of grounwater travel time and waste dissolution rates. To reduce the dissolution rate, some designs have included a limiting temperature in the long term, this limit being 106 °C after 200 (86), 500 (98), or 1000 (55) years of waste emplacement. The canister and overpack are assumed to have failed after those periods. This limitation would impose a very severe constraint in the maximum thermal loadings in the repository, particularly in the case of SF disposal (slow decay power) and a repository in basalt, where the temperature before waste emplacement is already 60 °C (99). Because of the uncertainties associated with this possible limit, it has not been considered in the thermal analysis calculations. This is an issue that deserves more investigation, since it could considerably affect the thermal design of the repository.

The same issue of waste dissolution long after emplacement affects another important component of the disposal system, namely the overpack design. Current overpacks are designed for long-term corrosion resistance (54,55), and consist of a layer of about 2.5 mm of Titanium surrounding a carbon steel reinforcement. As will be discussed in the results section these designs can result in costs for the overpacks required for the first repository of up to $1 billion. The Ti overpack, according to Westinghouse estimates (54,55) costs about $100 per Kilogram of Ti (manufactured). With a thickness of 2.5 mm it is expected to last well over 1000 years. Whether such an overpack is really necessary must definitely be investigated, for it represents a large percentage of the total disposal costs. In the case of HLW/FHLW in particular, where the radioactive source term has decayed to very low levels after 500 years of disposal, a 1000 years of overpack durability may be unnecessary. Also, an alternative material such as copper could be considered for the overpacks, since it is corrosion resistant and presumably not as costly as Ti.

Still in the overpack design another issue must be discussed, the thickness of the carbon steel reinforcement. The designs have been made for this reinforcement to provide structural integrity of the canister under the hydrostatic or lithostatic pressure that will exist in the repository. Design pressures range from 3 MPa in tuff to 16 MPa in salt, resulting in a canister thickness between 10 and 12 cm for a design in salt. An analysis is necessary to determine whether a canister full of consolidated fuel rods or borosilicate glass would collapse under compression, and if so, what would be the repercussions to the radionuclide leakage rates.

An additional issue in current repository designs that deserves some comments relates to the waste transfer and emplacement operations. The usual design for these operations is based in a manned vehicle to transport and load the waste canister in the borehole (100). Because of the radiation fields, this results in a relatively big vehicle with heavy shielding, which in turn results in larger openings in the disposal rooms. It is assumed in the present analysis that the transfer and emplacement operations are performed with remotely controlled vehicles, which would not require the heavy shielding and the bigger rooms. The loading of the canisters into the boreholes (in vertical emplacement) is not a complicated operation and the technology exists today for a remote-control design. This change could significantly reduce the emplacement costs or requirements, currently being estimated at 60 man-hours per borehole.

A last item that requires further research is the technique for borehole drilling in hard rock. The existing estimated costs for this operation in granite and basalt are around $2000 per meter of depth, depending on the diameter. Drill and blast techniques are assumed to be used, and since fracturing of the rock surrounding the borehole is not desirable, special blasting techniques must be used. Other methods such as using a especially designed saw to connect the previously drilled holes around the circumference of the borehole might result in lower manpower requirements and lower costs.

## C. Scenarios for the First Repository

The first repository will receive the oldest (and coolest) waste available, at least 15 years old, which means that the radiation levels and heat outputs will also be reduced. A total capacity of 72,000 MTHM, in agreement with reference repository designs, is assumed for the first disposal site. The disposal operations are assumed to take place for a period of 30 years, and the age of the waste at disposal varies throughout the operational period; for a repository openning in 2003, the first waste disposed would be over 29 years old and at the end of the operational period the waste would have been out of the reactors for 16 years. Details about estimates of installed nuclear power, fuel burnup and annual spent fuel production that permitted the calculation of the variable age of the waste at disposal can be found in reference 88.

All scenarios analyzed assume that the proposed date for starting operations of the MRS facility (1998) applies. The repository operations start in 2003 in the reference case, although this date is allowed to be delayed in the economic model with the purpose of reducing the thermal output of the canisters when necessary, to optimize the total system cost. It is assumed that the flow rate of spent fuel to the MRS and waste disposal occurs in two phases; phase 1 covers the first five years of operations, with a spent fuel (or equivalent waste) receiving rate of 1310 MTHM per year, and phase 2 covers the remaining 25 years of storage or disposal operations with a receiving rate of 2620 MTHM per year. The receiving rates have been calculated so that a total of 72,000 MTHM are processed in the lifetime (30 years) of the first disposal site. Phase 1 has a receiving rate of one half the rate in phase 2, consistent with DOE predictions. The scenarios for the once-through cycle include:

- MRS is located in Tennessee; the spent fuel is consolidated at the MRS site. Transportation of the consolidated spent fuel from the MRS to the repository is scheduled one year ahead of disposal.

- The MRS is located in Tennessee but the spent fuel is consolidated at the packaging plant in the repository site.
- The MRS is co-located with the repository and consolidation of the spent fuel is performed before the storage begins, so that consolidated SF is stored in the MRS.
- The MRS is co-located with the repository and stores unconsolidated spent fuel. Consolidation operations take place right before disposal.

The comparison of the results of the economic analysis for the different scenarios will provide information about differences in cost between transporting or storing consolidated or unconsolidated spent fuel. Conclusions about the effect of the MRS location will also be obtained. Three different canister sizes for disposal are considered in each scenario, namely canisters containing 3, 6 or 12 consolidated assemblies. The number of canisters disposed per year for the three options is shown in Table 1.

Similarly, four scenarios are defined for the reprocessing cycle:

- The MRS is located in Tennessee and the spent fuel is consolidated before storage.
- The MRS is in Tennessee but consolidation is not performed, so that unconsolidated assemblies are stored and transported.
- The MRS is co-located with the repository and consolidation is done before storage and reprocessing.

- The MRS is co-located with the repository but the spent fuel is never consolidated.

The reprocessing operations are always assumed to be one year ahead of disposal. If the disposal is further delayed, so is the reprocessing such that only spent fuel is stored in the MRS, but not the reprocessed waste. For the nine possible canister designs for HLW, the number of boreholes required per year is also indicated in Table 1. Note that in the reprocessed waste case, the numbers given in the table are the number of boreholes; the number of canisters would be 3 times larger since 3 canisters are emplaced per borehole. The choice of giving the number of boreholes is to provide the bases for comparison with the number of (the 3 times larger) canisters of spent fuel. The TRU waste drums are not emplaced in boreholes, bur rather they are simply piled in excavated rooms. The numbers in the table for TRU waste are actual number of drums, not boreholes.

The same scenarios defined for the reprocessing cycle apply in the case of the fractionated high-level waste cycle. The only difference is in a second period of operations for the fractionation cycle, in which the Cs/Sr is disposed. The storage of SF before reprocessing and the disposal of the FHLW occurs under the same schedules given in the regular reprocessing cycle. The Cs/Sr is used or stored during the 30 years of disposal of the FHLW and is disposed in another 30-year period after all the FHLW is disposed. The number of boreholes (sets of three canisters) required in the fractionation cycle is also given in the table. Because of uncertainties about the demand for Cs and the exact

TABLE 1. Number of emplacement boreholes required in the two operational phases, by cycle

| Cycle | Number of boreholes/year[a] Phase 1 | Phase 2 |
|---|---|---|
| SF 3 a/c[b] | 947 | 1894 |
| 6 a/c | 474 | 947 |
| 12 a/c | 237 | 474 |
| Hardware | 119 | 238 |
| Reprocessing | | |
| HLW 3010[c] | 827 | 1654 |
| 3015 | 552 | 1104 |
| 3020 | 414 | 818 |
| 4010 | 465 | 930 |
| 4015 | 310 | 620 |
| 4020 | 233 | 466 |
| 5010 | 298 | 596 |
| 5015 | 199 | 398 |
| 5020 | 149 | 298 |
| Hulls/hardware | 222 | 444 |
| TRU drums | 1310 | 2620 |
| Fractionation | | |
| FHLW 3010 | 736 | 1472 |
| 3015 | 491 | 982 |
| 3020 | 368 | 736 |
| 4010 | 414 | 818 |
| 4015 | 276 | 552 |
| 4020 | 207 | 414 |
| 5010 | 265 | 530 |
| 5015 | 177 | 354 |
| 5020 | 133 | 266 |
| Hulls/Hardware | 222 | 444 |
| TRU drums | 1310 | 2620 |
| Cs/Sr | 433 | 433 |

[a]The number of canisters for SF coincides with the number of boreholes, and for HLW/FHLW is three times larger than the number of boreholes.

[b]a/c - spent fuel assemblies per canister.

[c]The first two digits indicate the diameter (in cm) of the canister and the rest the waste concentration (in w/o) in the glass.

concentration of Cs/Sr in the canisters, a total of 433 boreholes (1300 canisters of 1.2 m in length) is assumed, which corresponds to the reference value of 1.7-2 $ft^3$/MTHM of solidified Cs/Sr product.

# IV. REPOSITORY THERMAL ANALYSIS

## A. Introduction

One of the main cost components of the repository will be the excavation cost, proportional to the excavated disposal surface. Aside from construction feasibility considerations, the maximum allowable thermal loading will be the chief factor determining the disposal area requirements. It becomes therefore necessary to perform an analysis of the allowable thermal loadings and their sensitivity to significant parameters.

Previous repository cost analyses (57,68,69,72-75,101,102) have used a fixed thermal loading, expressed in units of power per unit of surface, although some authors (48,85-87,77,78,103,104) have pointed out or even studied the effect of some other parameters in the permissible density of disposal. In the present work, the thermal analysis has been performed in order to calculate the repository thermal loadings as a function of important parameters such as the age of the waste at disposal, the waste form, canister size and waste concentration, thermal properties of the host rock, excavation extraction ratio, and the possibility of waste retrieval. As of today, a decision concerning all these variables has not been made and a host rock has not been chosen. Including the range of possibilities being considered for these parameters in the thermal analysis will provide the bases for comparison of the different options, as well as an estimate of the uncertainty associated with the thermal loadings.

A precise thermal analysis of the repository requires the modeling of a large region and the use of a numerical technique for solving the heat transfer equations. A very fine mesh is required to analyze the volume corresponding to the waste canisters and their immediate surroundings. Such a model results in a large computer code whose CPU running times become prohibitive when it is used in a parametric analysis, in which many different situations have to be studied.

Instead, a simplified, approximate model has been used in this analysis, in which the repository region is divided into three ranges:

- Very-Near-Field (VNF), corresponding to the borehole region, including the waste canister.
- Near-Field (NF), corresponding to the room and pillar environment.
- Far-Field (FF), corresponding to the range of the whole repository, from repository horizon to the surface.

The division into these particular three ranges has been commonly used in repository analysis for flow, mechanical and thermal behavior. The acceptability of decoupling the three ranges in a thermal analysis has also been discussed (104,105).

The following sections in this chapter include a discussion of the thermal constraints applicable to each of the three ranges, the properties of the different host rocks considered for a repository location, and the description and results of the thermal analysis.

## B. Thermal Constraints

The repository thermal constraints include a set of criteria or limits that must not be exceeded in order to preserve the physical or chemical integrity of the components of the multiple barrier waste isolation system, as well as the physical integrity of the repository during the operational period. The set of limits are expressed in the form of maximum admissible temperatures in the different materials and maximum permissible strength-to-stress ratios for stability of the room and pillar system.

### 1. Very-Near-Field constraints

A compilation of the most important VNF thermal limits is listed in Table 2, where the criteria determining the thermal limits are also indicated.

TABLE 2. Summary of Very-Near-Field thermal constraints

| Material | Limit | Criterion | Reference(s) |
|---|---|---|---|
| Spent Fuel | 375 °C | Clad stress-rupture | 46,106,107 |
| HLW Glass | 500 °C | Devitrification | 33,107,108 |
| HLW Glass | 20 % waste conc. | Stability | 109,110 |
| SS Canister | 375 °C | Structural changes | 33,48,108 |
| Bentonite | 300 °C | Chemical stability | 55,108 |

With regards to the SF limit, some authors used a 200 or 250 °C limit to prevent oxidation of the fuel material. Recent canister design studies, however, have considered the 375 °C limit under the assumption that the SF canister will be filled with an inert gas and oxigen will not be available for oxidation.

2. Near-Field constraints

The NF limits are designed to maintain the physical integrity of the rooms and pillars in the repository during the operational period. They are defined in terms of strength safety factors to ensure stability, or maximum rock T. Although some of these limits are of a mechanical nature, they may restrict the thermal loadings of the repository to prevent the creation of excessive thermal stresses that could violate the minimum safety factors. A summary of the more relevant NF limits is listed in Table 3.

It must be pointed out that the temperature limit listed for granite and basalt will never become a constraint for the standard disposal schemes, since the bentonite limit is always lower. Although in this work it has been chosen not to set any limit in the maximum temperature of tuff, it must be noted that drastic changes in thermal properties occur when the temperature in the rock exceeds that of the boiling point of water at the hydrostatic pressure corresponding to the depth of the repository. Tuffaceous formations have in general a large water content and dehydratation takes place above the water boiling temperature.

Maximum temperatures of the drift surfaces are often specified as a NF limit, in order to maintain safe working conditions and the

TABLE 3. Summary of Near-Field constraints

| Material | Limit | Criterion | Reference(s) |
|---|---|---|---|
| Tuff | Min. SSR=1.5[a] Pillar midheight | Pillar stability | 111 |
| Granite Basalt | Min. SSR=2 Pillar midheight | Pillar stability | 33,59,108 |
| Granite Basalt | Min. SSR=2 1.5 m of opening | Room stability | 33,59,108 |
| Salt | Maximum room closure = 15 % | Room stability and retrievability | 101 |
| Salt | 250 °C | Decrepitation | 104,106,108 |
| Granite | 350 °C | Fracture | 104,106,112 |
| Basalt | 350 °C | Fracture | 108 |
| Tuff | No limit | | 111,112 |

[a]SSR - Strength-to-Stress Ratio.

possibility of performing retrieval operations. Typical temperatures are set at 50 °C, although in some designs, particularly in basalt formations, the initial temperature (before waste disposal) at the repository horizon already exceeds this limit. In the present work, the temperature limit for the drift surfaces is not considered in the calculation of the permissible thermal loadings. If excessive temperatures were to be produced in the drift surfaces because of high disposal densities, it is assumed that the ventilation system will be capable of maintaining safe working conditions in the repository.

3. Far-Field constraints

The FF limits refer to the maximum tolerable changes produced by the repository in the geologic, hydrologic, and geochemical systems. Some of these constraints are concerned with the amount of fracturing of the rock, temperature increase in aquifers, distortion of the original permeability of the geologic formation, size of the unperturbed rock cover, and ground water travel time to accessible environment. All these variables are extremely site-dependent, making nearly impossible their inclusion in a generic study.

Two other constraints have also been specified regarding the degree of environmental distortion. They are the maximum surface uplift due to thermal expansion of the host rock and maximum surface temperature increase. Recommended values are 0.5 °C for the temperature rise and 1.5 meters for the surface uplift. The surface uplift limit is often more restrictive than the maximum T increase (101).

## C. Host Rock Thermal Properties

The properties of the repository medium play an essential role in determining the acceptable thermal loadings. The thermal expansion coefficient, for instance, is very important in calculating the surface uplift, and the thermal conductivity and the specific heat will determine the maximum disposal density that permits compliance with the NF limits. Furthermore, even though the VNF limits refer only to the canister region, the thermal properties of the host rock will influence the temperature history of the borehole surface, thus determining the boundary condition of the VNF region.

Because they affect each of the three levels in which the thermal analysis is structured, the thermal properties of the host rock are key parameters in this study. A careful estimation of these properties becomes necessary.

Naturally, the thermal properties change from site to site, even for the same type of formation, due to variations in rock composition. These composition changes occur also within the range of a single repository site, and it is impossible to select a precise set of property values. Therefore, it has been attempted in the present work to define a range of values for the thermal properties of the four different host rocks.

There exist numerous literature sources on measurements or estimates of the thermal properties of salt, basalt, granite and tuff rocks. They cover a very large spectrum of values, referring either to generic rocks or samples from specific locations. In order to narrow the range of values to a reasonable interval, only the more recent sources are used, and when available, a higher importance is given to measured values in proposed repository locations. A short discussion for each particular rock follows:

- BASALT - Data exist for the Columbia Plateau region, although variations occur from formation to formation. Most of the data come from the Pomona and Umtanum flows (58,113,114). Mean values and their standard deviations have been estimated from the data in the different sources to define the range of the thermal properties to be used in the present thermal analysis.

- GRANITE - Most of the data available for granite are generic (57,104,115) because a possible repository location in granite has not been selected yet. Mean values and standard deviations have again been calculated except for the density, because of the uniformity of the data used.
- SALT - A collection of experimental data exists from proposed repository locations (95). Except for the thermal conductivity, these experimental results are in very good agreement and they are used in the analysis. Thermal conductivity measurements are spread over a considerable range, indicating that further experiments should be performed. Because salt thermal conductivity is strongly dependent on temperature, values covering the expected temperature range have been chosen from the recommended corrected experimental results (95).
- TUFF - Choosing a set of values for the thermal properties of tuff presents additional problems, because of the drastic difference in properties when the rock dehydrates. In addition, two possible repository locations have been identified, the first at a depth between 300 and 400 m. and the second about 700 m. deep. The difference in depth changes the boiling temperature of water considerably, thus requiring

a separate analysis. Data from the Paintbrush tuff (300-400 m.), Yucca Mountain, Nevada, with a hydrostatic boiling point of 100 °C have been used as a first option. Because of the low boiling point, dehydrated tuff properties were chosen. The second option corresponds to a depth of 700 m., where the hydrostatic boiling point is at 225 °C. Because only a small fraction of the repository is expected to be above that temperature, an average between wet and dry properties have been selected using data for the Bullfrog formation in Yucca Mountain, Nevada (116,117).

The thermal properties for the four different rocks that have been used in the thermal analysis are summarized in Table 4. Estimates of the standard deviations are given along with the mean values. When experimental data were very uniform, no standard deviation was estimated, and for thermal conductivity in salt only the ends of the range are listed. For tuff, no standard deviations were estimated; instead, the set of values for the two different cases mentioned are listed.

## D. Development of the Analysis

The thermal analysis of the repository has been performed for two waste types, SF and HLW, and four rock types. In each case, the study for the three levels (VNF, NF, and FF) and the sensitivity to different parameters has been carried out.

The VNF part is expected to give a maximum heat load per canister

TABLE 4. Host rock properties[a]

| Rock | $\alpha$ 1/10$^6$ K | Cp J/Kg-K | $\rho$ Kg/m$^3$ | k w/m-K | $\nu$ |
|---|---|---|---|---|---|
| Basalt | 6.78 (1.2)[b] | 904 (103) | 2819 (56) | 1.3 (0.2) | 0.25 |
| Granite | 7.26 (1.19) | 865 (64) | 2650 | 2.78 (0.23) | 0.19 |
| Salt | 41.8 (3.6) | 910 (9) | 2190 | 3.6 - 5 | 0.36 |
| Tuff[c] | 7.55 (1.05) | 1600 | 2250 | 2.0 | 0.25 |
| Tuff[d] | 7.55 (1.05) | 850 | 2200 | 1.55 | 0.25 |

[a]$\alpha$ - thermal expansion coefficient; Cp - specific heat; $\rho$ - density; k - thermal conductivity; $\nu$ - Poisson ratio.

[b]Values in parentheses are standard deviations.

[c]Bullfrog Tuff.

[d]Paintbrush Tuff.

and the maximum permissible temperature at the surface of the canister. The NF part results in a minimum pitch between canisters necessary to meet the NF limits and the maximum temperature at the surface of the canister required by the VNF. The VNF results are used as input information for the NF calculations. The FF range is decoupled from the other two ranges, resulting in the maximum loading of waste per unit surface of the entire repository, which must be compared with the result obtained from the NF. The more restrictive of the two values is the maximum allowable density of disposal.

In all the heat transfer calculations, a decaying heat source has been used, with data for PWR spent fuel and reprocessed high-level waste decay powers (104,118). Equations 4.1 to 4.3 give the decay power of SF and equations 4.4 to 4.6 the decay power of HLW. The power, expressed in watts, is normalized in all cases to 1 metric ton of heavy metal (MTHM), and time is expressed in years after discharge of the SF from the reactor.

$$Q = 550 \cdot EXP(1/(0.223 + 0.117 \cdot t)) \qquad t \leq 30 \text{ years} \qquad (4.1)$$

$$Q = 930 \cdot EXP(-0.0231 \cdot t) + 180 \cdot EXP(-0.0531 \cdot t) + 209 \cdot EXP(-0.0025 \cdot t) + 26 \qquad 30 \leq t \leq 400 \text{ years} \qquad (4.2)$$

$$Q = 10 \cdot EXP(-2.48\ 10^{5} \cdot t) + 16 \cdot EXP(-0.000105 \cdot t) + 132 \cdot EXP(-0.001513 \cdot t) \qquad t \geq 400 \text{ years} \qquad (4.3)$$

$$Q = 950 \cdot EXP(-0.0231 \cdot t) + 62 \cdot EXP(-0.0433 \cdot t) + 62 \cdot EXP(-0.0277 \cdot t) + 645 \cdot EXP(-0.2039 \cdot t) \qquad t \leq 30 \text{ years} \qquad (4.4)$$

$$Q = 1042 \cdot EXP(-0.02345 \cdot t) + 4.5 \qquad 30 \leq t \leq 300 \text{ years} \qquad (4.5)$$

$$Q = 4 \cdot EXP(-0.001513 \cdot t) + 2 \cdot EXP(-0.000105 \cdot t) \qquad t \geq 300 \text{ years} \qquad (4.6)$$

Figure 5 shows the power history of SF and HLW as a function of time. Fractionated high-level waste decay heats have not been included in this section because they are not used in the thermal analysis. The results for HLW have been applied to the case of the FHLW.

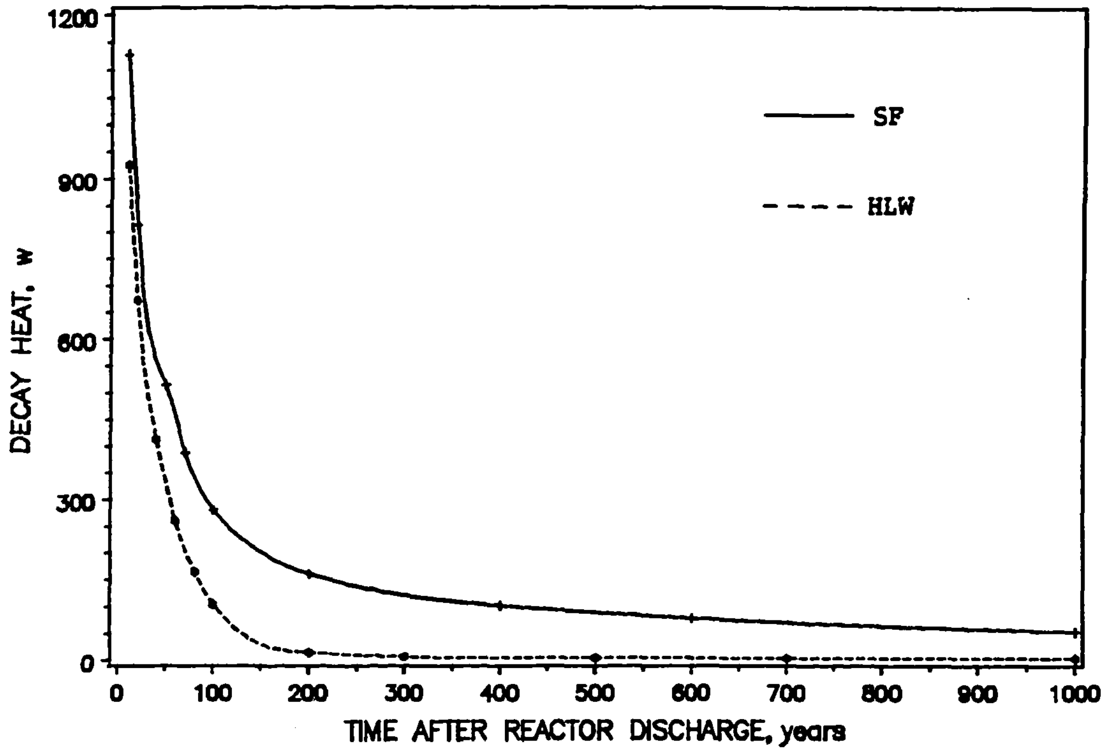


FIGURE 5. Spent fuel and High-level waste decay powers

1. VNF calculations

a. VNF calculations for SF    Proposed canister and borehole designs cover a wide range of possibilities, from canisters containing a single fuel assembly to canisters containing 12 assemblies, from air-filled to metal-filled canisters. Because of their low thermal output, canisters containing only one fuel assembly (about 0.47 MTHM) do not come close to the VNF thermal restrictions. This type of design, however, would require a large number of canisters, which would be expensive. More practical designs consider the consolidation of the fuel rods from several fuel assemblies into the same canister, thus reducing the required number of canisters. Most of these designs are perfectly compatible with the VNF restrictions.

Only the case of consolidated fuel rods is considered in the present study and, following the trend of the more recent canister designs (53-55), three different canister sizes are considered:

1. Canister of 32 cm ID, containing consolidated fuel rods from 3 (3 a/c) assemblies.[1]
2. Canister of 44 cm ID, containing rods from 6 assemblies.
3. Canister of 60 cm ID, containing rods from 12 assemblies.

The canisters are 4.1 m long in all three cases and the active (heat generating) length is 3.66 m. The possibility of metal-filling the canisters has not been considered because of its apparently small advantage. The purpose of filling the spaces between rods with metal is to enhance the effective thermal conductivity and reduce the peak temperature at the center of the canister. The consolidated designs, however, where the rods are in contact with each other and the canister has radial reinforcements, appear to have a relatively small temperature drop from center to surface (106,107), making unnecessary the use of a metal filling. Metal filling might be considered again if it becomes necessary to use this method to exclude air.

The possibility of an air gap surrounding the canister for the purpose of retrievability (and to facilitate the emplacement

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[1] PWR fuel assemblies are considered throughout this study.

operations, as well) has been analyzed for each canister size. A constant gap clearance of 6 cm has been used, this distance being determined as an optimum from gap size analysis calculations (See Appendix A).

The borehole designs used are shown in Figure 6, and the dimensions of the radii for each canister size are listed in Table 5. It must be noted that the thicknesses of overpacks and sleeves are relatively small and the same in all cases. In a particular design, these thicknesses would depend upon the existing lithostatic pressure. A repository designed in tuff would result in pressures smaller than in other rocks, thus requiring thinner overpacks and sleeves (55,112). Using smaller thicknesses than required for overpack and sleeve is a conservative approach from the thermal analysis standpoint, and consequently the design values for tuff are used for disposal in other rocks as well.

As seen in Figure 6 all designs include bentonite filling the gap between overpack (sleeve) and host rock. Bentonite has been chosen instead of crushed rock (cheaper) or other filling materials (with possible better thermal conductivity) because of its good characteristics as a buffer material. In this regard, bentonite acts as a zeolite and a retardant for fission product leakage from the borehole. An equal thickness of 12 cm is used in all designs and it has been selected from recommended values in the literature (102,108).

The VNF analysis consisted of determining the maximum heat loads per canister and the surface temperature necessary to ensure compliance

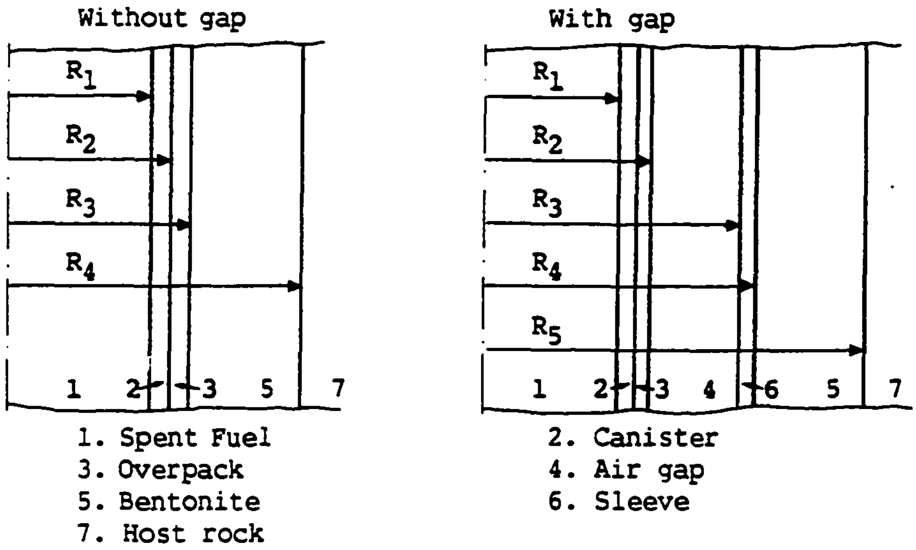


FIGURE 6. Borehole designs for spent fuel

TABLE 5. Dimensions for borehole designs in spent fuel

| Design | $R_1^a$ | $R_2$ | $R_3$ | $R_4$ | $R_5$ |
|---|---|---|---|---|---|
| 3 a/c with gap | 0.16 | 0.19 | 0.25 | 0.26 | 0.38 |
| 3 a/c no gap | 0.16 | 0.17 | 0.19 | 0.31 | |
| 6 a/c with gap | 0.22 | 0.25 | 0.31 | 0.32 | 0.44 |
| 6 a/c no gap | 0.22 | 0.23 | 0.25 | 0.37 | |
| 12 a/c with gap | 0.30 | 0.33 | 0.39 | 0.40 | 0.52 |
| 12 a/c no gap | 0.30 | 0.31 | 0.33 | 0.45 | |

[a]Dimensions in m.

with the VNF constraints for all six designs. A detailed description of the semi-analytical model used is offered in Appendix A. The thermal conductivity of the different materials involved in the VNF range had to be estimated. The effective thermal conductivity inside the canister is given in equation 4.7. The detailed estimation of this thermal conductivity is presented in Appendix A.

$$k = 0.6371 + 3.0628\ 10^{-8}\ T^3\ \text{w/m-K} \qquad (T \text{ in } °C) \qquad (4.7)$$

The thermal conductivity of the bentonite buffer was estimated at 1 w/m-K (119,120) and constant over the temperature range of interest. Because of the high thermal conductivity of the materials employed in the canister wall (stainless steel), overpack (stainless steel and titanium), and sleeve (carbon steel), they were not included in the heat transfer calculations. A constant 1 °C temperature drop accross each of them was considered in all the cases.

b. VNF calculations for High-level waste In order to analyze the effect of the canister size on the permissible thermal loadings, three different sizes were chosen, covering the range of existing proposed designs. There is an additional variable in the case of glassified HLW affecting the heat content, which is the concentration of waste in the glass. For each canister size three different concentrations were studied.

The length of the canisters was set at 1.3 m, with an active length of 1.2 m. Longer glass blocks are normally not recommended, because the fracturing of the glass after forming is proportional to its size. Table 6 lists the different combinations of size and concentration studied and the amount of waste (in equivalent MTHM) contained in the canister.

The highest concentration was set at 20 % by weight for stability

TABLE 6. Combinations of canister size and concentration

| Case | Canister Radius (m) | Waste Oxides Concentration w/o | Waste content (MTHM) |
|---|---|---|---|
| 1 | 0.15 | 10 | 0.5278 |
| 2 | 0.15 | 15 | 0.7917 |
| 3 | 0.15 | 20 | 1.0556 |
| 4 | 0.20 | 10 | 0.9382 |
| 5 | 0.20 | 15 | 1.4073 |
| 6 | 0.20 | 20 | 1.8764 |
| 7 | 0.25 | 10 | 1.4660 |
| 8 | 0.25 | 15 | 2.1990 |
| 9 | 0.25 | 20 | 2.9320 |

considerations, whereas the lowest one was set at 10 w/o in waste oxides, corresponding to a roughly 8 w/o fission product concentration. A lower concentration would result in an excessive number of canisters.

The procedure in the VNF analysis for HLW is similar to that described for SF. Borehole designs were made for all canister sizes with and without the presence of an air gap, and a 12 cm thick bentonite buffer was also used in all cases. The borehole designs are shown in Figure 6 and their dimensions are listed in Table 7.

Again, a uniform gap size of 6 cm was used, and the thickness of overpack (sleeve) was chosen with the same approach that was used in the SF case. A temperature-independent thermal conductivity of 1 w/m-K was used for the waste glass (23,24,121,122) as well as for the buffer material.

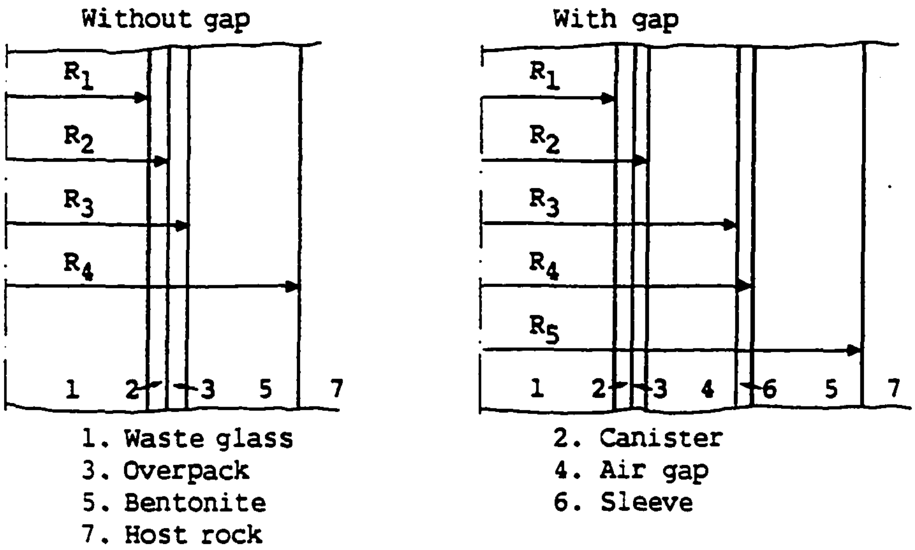


FIGURE 6. (Repeated) Borehole designs for High-level waste

TABLE 7. Dimensions for borehole designs in HLW

| Design | $R_1^a$ | $R_2$ | $R_3$ | $R_4$ | $R_5$ |
|---|---|---|---|---|---|
| 0.3 m with gap | 0.15 | 0.18 | 0.24 | 0.25 | 0.37 |
| 0.3 m no gap | 0.15 | 0.16 | 0.18 | 0.30 | |
| 0.4 m with gap | 0.20 | 0.23 | 0.29 | 0.30 | 0.42 |
| 0.4 m no gap | 0.20 | 0.21 | 0.23 | 0.35 | |
| 0.5 m with gap | 0.25 | 0.28 | 0.34 | 0.35 | 0.47 |
| 0.5 m no gap | 0.25 | 0.26 | 0.28 | 0.40 | |

[a]Dimensions in m.

## 2. Near-Field calculations

In the NF part of the thermal analysis the minimum required pitch between canisters was calculated such that the maximum temperature criteria imposed by the VNF and NF constraints were met. From the calculated minimum pitch, the thermal loading in power or mass of heavy metal per unit surface can be inferred. A semi-analytical three-dimensional superposition model was developed to perform these calculations. The model is developed in detail, and its accuracy checked, in Appendix B. The model uses temperature-independent thermal properties. The calculations were performed for SF and HLW, for all borehole designs, and for disposal in the four different rocks. In all cases, the required pitch was estimated for different ages of the waste at disposal, starting with 10 year-old waste.

In some situations such as for very old waste or for very small canister heat loadings, the minimum pitch from the thermal standpoint would become unacceptably small for constructability considerations. In those cases, a minimum pitch limit was set equal to 1 m plus 1 borehole diameter. This criterion sets a minimum unperturbed rock zone of 1 m between boreholes; smaller distances could easily result in excessive rock fracturing.

The baseline cases were calculated using the mean values of the rock thermal properties, as listed in Section C. Because the thermal loading depends upon the room-to-room distance, a value for this distance had to be established as input for the NF study. Based on recommended maximum excavation extraction ratios,[2] 20 % for tuff and 25 % for the other rocks (44,112), and for the 3 m wide rooms, the room-to-room distance was set at 15 m for tuff and 12 m otherwise. Another

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[2] Extraction ratio is the volume of the room over the volume of room plus pillar.

important variable that has to be determined is the initial temperature of the host rock at the repository horizon. The values selected are 60 °C for basalt and 35 °C for the other rocks (102,112). The initial temperature of the rock depends upon the depth of the repository. The values chosen correspond to the deepest proposed repository location in each of the rocks, which is a conservative approach, since shallower repositories would have a lower initial temperature.

After all the baseline cases had been calculated, a sensitivity study with respect to parameters was performed. Changes in the permissible NF thermal loadings due to variations in density (basalt), specific heat and thermal conductivity (all rocks) were evaluated. Two sets of properties were studied for tuff, one corresponding to a repository in the Paintbrush formation and another for a repository in the Bullfrog formation, instead of performing a sensitivity analysis with respect to a single mean value. The same approach was taken when studying the effect of the thermal conductivity in salt rock. Because of the wide range of values for this variable in salt, two sets of cases were run, one with a thermal conductivity of 5 w/m-K and another with 3.6 w/m-K. The response of the NF loading to increasing the room-to-room distance (decreasing the extraction ratio) was also studied, by calculating the change in pitch when increasing the pillar width 3 and 6 m.

## 3. Far-Field calculations

The surface uplift criterion was used to calculate the maximum thermal loading that the FF restrictions permit. A semi-analytical model using constant rock properties was used, as described in Appendix A. Application of the model results in the FF loading expressed in permissible power or mass of heavy metal per unit surface. It must be noticed that in this range, variables such as borehole dimensions or extraction ratios do not play any role. The resulting thermal loading is an average over the entire repository surface.

The analysis was applied to the four rocks for disposal of SF and HLW, and for each case the variation of the load with respect to the age of the waste at emplacement was studied. Because the average FF temperatures are low when compared to the temperatures in the NF region, the thermal properties were accordingly adjusted for those rocks that show a very strong temperature dependence, i.e., salt and tuff.

The sensitivity of the FF thermal loadings to variations in depth of the repository and rock thermal properties (thermal expansion coefficient in particular) was also determined. When the results of the NF and FF steps in the thermal analysis are put together to determine the resulting power (or waste mass) per unit surface, an approximation is made in the definition of the "unit surface"; the unit surface in the NF refers to room and pillar, whereas in the FF the surface includes also corridors and other non-disposal areas of the underground facility. It is a conservative approach to neglect the correction in the FF unit surface.

## E. Thermal Analysis Results and Discussion

### 1. Very-Near-Field

a. Spent fuel The fuel temperature limit of 375 °C was the limiting condition only in the case of 12 assemblies per canister for fuel up to 15 years of age at emplacement with no gap around the canister and up to 35 years of age when an air gap is included in the borehole design. For disposal of older fuel the bentonite temperature limit of 300 °C becomes the limiting condition. The bentonite constraint is always the limit for disposal of canisters containing 3 or 6 SF assemblies.

When the bentonite limit applies, the permissible rock temperature at the surface of the borehole is a linear function of the heat content in the canister. In these cases, this rock temperature is never severely restricted, and is always above 200 °C. (It must be recalled that the waste is at least 10 years old at disposal.)

The only serious restrictions in borehole surface temperature occur when the fuel temperature is the limiting parameter, and especially for the air gap design. In the last situation, and because the power density in the canister is very large (case of 12 assemblies), the temperature drop in the canister is considerable, thus reducing the canister surface temperature. The principal heat transfer mechanism through the gap is radiation, and the relatively low canister surface temperature produces a big temperature drop through the gap.

In fact, for designs with 3 or 6 assemblies per canister, the air gap results in a permissible rock temperature that is less restricted than that in the absence of a gap. Only for the high volumetric heat sources corresponding to short cooled canisters with 12 assemblies, does the presence of the air gap result in a more severe restriction. In the other situations the increase in heat transfer surface in the bentonite buffer when including the air gap has a larger effect in reducing the temperature drop than has the gap thermal resistance in increasing it.

Table 8 lists the resulting permissible rock temperatures when the bentonite constraint is the limiting factor, whereas Figure 7 shows the maximum rock temperature for the case of 12 assemblies per canister when the fuel temperature dominates the VNF restrictions. Besides the temperature limits determined under fuel and bentonite constraints, there is the additional 250 °C limit when the host rock is salt.

<u>b. High-level waste</u> In almost all situations the bentonite temperature restriction is the real VNF thermal limit. Only for the 50 cm ID canister size at very high power densities (combination of short cooling and high waste concentration) does the maximum glass temperature of 500 °C become a constraint. In any case, for the range of canister sizes and waste concentration in the glass that have been studied, the VNF thermal restriction does not limit the canister power content, but rather the temperature at the boundary of the borehole. It has been chosen to limit that temperature instead of constraining the canister thermal power because the maximum acceptable rock

TABLE 8. Permissible borehole rock temperatures for SF disposal

| Design | Maximum permissible rock temperature (°C) | Age of waste (years) |
|---|---|---|
| 3 a/c with gap | $300 - 0.0213 \cdot Q^{a}$ | ≥ 10 |
| 3 a/c no gap | $300 - 0.0275 \cdot Q$ | ≥ 10 |
| 6 a/c with gap | $300 - 0.0179 \cdot Q$ | ≥ 10 |
| 6 a/c no gap | $300 - 0.0220 \cdot Q$ | ≥ 10 |
| 12 a/c with gap | $300 - 0.0147 \cdot Q$ | ≥ 35 |
| 12 a/c no gap | $300 - 0.0174 \cdot Q$ | ≥ 15 |

[a]Q given in watts per canister.

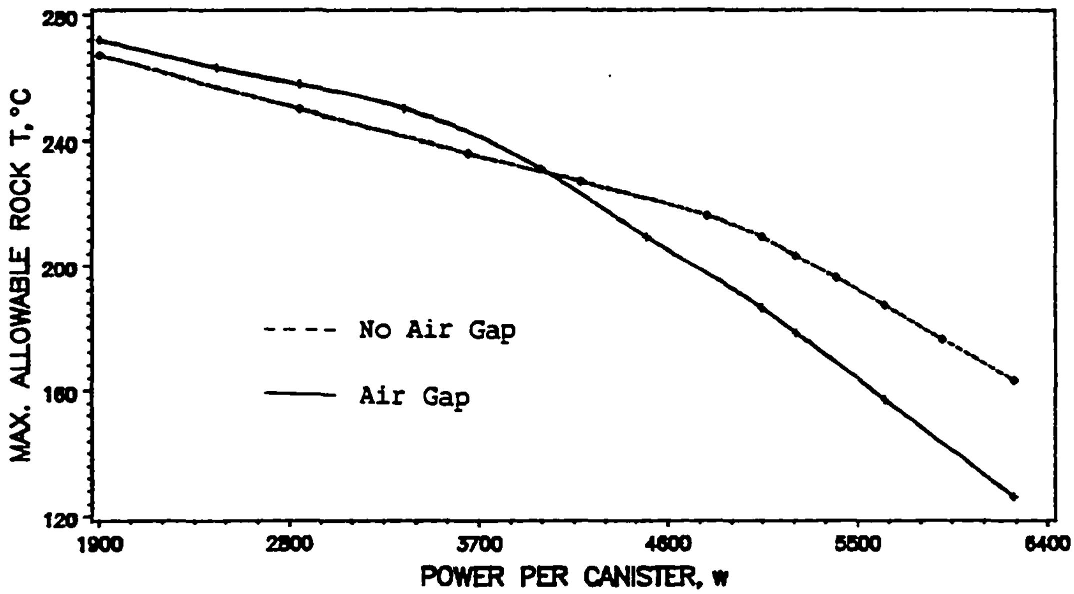



FIGURE 7. Permissible borehole rock temperatures for shortly cooled SF with 12 assemblies per canister

temperatures turn out to be in a very reasonable range and can be adjusted in the NF, by adjusting the canister pitch. That is to say that in the range of canister powers analyzed, the VNF restrictions can be translated into a NF maximum rock temperature at the borehole wall.

When bentonite is the limiting condition, the maximum permissible rock temperature at the borehole boundary can be expressed as a linear function of the thermal power in the canister. A different linear function is obtained for each canister size, regardless of the waste concentration in the glass. Age of the waste and concentration determine the heat output in a canister, for any given size, so that the maximum temperature of the rock is not a 3-parameter model (age, concentration and size), but only a 2-parameter system, canister thermal power and size.

The situation where the glass temperature restricts the VNF reduces to a very narrow range of canister powers, and only for a canister size of 50 cm ID. For simplification, a linear approximation has also been used to relate the acceptable rock temperature to the canister heat output. Expressions of the permissible rock temperatures for the different cases are listed in Table 9.

Air gap effects are similar to those observed for SF disposal. When the waste temperature limit is the constraint, the presence of an air gap requires lower rock temperatures. When bentonite temperature is the constraint, the air gap results in a beneficial effect.

## 2. Near-Field results

A problem appeared for presenting the results of the NF analysis, since there were three possible variables that could be used: thermal power per unit surface, waste mass per unit surface, and canister

TABLE 9. Permissible borehole rock temperatures for HLW disposal

| Canister ID (m) | Maximum permissible rock temperature (°C) | Applicable range |
|---|---|---|
| 0.30 with gap | $300 - 0.0538 \cdot Q$[a] | All Q |
| 0.30 no gap | $300 - 0.0678 \cdot Q$ | All Q |
| 0.40 with gap | $300 - 0.0459 \cdot Q$ | All Q |
| 0.40 no gap | $300 - 0.0557 \cdot Q$ | All Q |
| 0.50 with gap | $300 - 0.0401 \cdot Q$ | $Q \leq 2300$ |
| | $589 - 0.1661 \cdot Q$ | $Q \geq 2300$ |
| 0.50 no gap | $300 - 0.0473 \cdot Q$ | $Q \leq 2350$ |
| | $302 - 0.0480 \cdot Q$ | $Q \geq 2350$ |

[a]Q expressed in watts per canister.

pitch. They are all equivalent, and the first two variables are calculated from the canister pitch, which is what is in fact calculated in the NF model. The surface density variables are calculated by dividing the heat output (or mass of waste) per canister by the canister pitch and the room-to-room distance. The more direct variable for expressing the NF results would have been the canister pitch, but it could have not been used meaningfully for expressing the FF results. Within the NF range the use of the canister pitch could pose some formal problems as well, for the room-to-room distance would not be implied in the presentation of results.

The choice had to be made between using thermal power or waste mass in the density of disposal expression. Because the waste to be disposed of is always counted in MTHM, not in thermal power (thermal power is time-dependent, and mass is not) it is more meaningful to express NF results in terms of mass of waste per unit surface. However, when using the waste mass per unit surface in disposal of HLW, no easy expressions could be found for density of disposal as a function of canister power (or age) without considering both canister size and waste concentration as parameters. In other words, for each rock 9 different expressions had to be developed. Because of this added complexity, the other alternative was chosen, and thus the NF thermal loading results are expressed in units of thermal power (w) per unit surface ($m^2$). That permits a great simplification when expressing the results for HLW, because the thermal loading can be expressed as a function of the canister heat content at the time of emplacement with a single expression in each host rock, regardless of canister size or concentration. Already implied in the preceding discussion is the use of the thermal power per borehole at emplacement, which is inversely proportional to the age of the waste at disposal. Again, avoiding the use of canister size and concentration as parameters in HLW disposal justifies the use of this variable.

a. Spent-fuel Considerably different values for the 3 different canister designs were found, and an independent expression for each design was sought, by performing a least-squares fit to the data obtained in the individual runs of the NF model. The dependence of the NF thermal loading upon the canister (or borehole, since in SF disposal there is one canister per borehole) heat output at the time of disposal is very similar in all cases. At values approaching the maximum heat content per canister, corresponding to early disposal, the thermal loading is at its peak for the 3 and 6 a/c designs. For early disposal, a large fraction of the heat is generated by short-lived nuclides, which have decayed away by the time the rock reaches its limiting temperature at the borehole surface, thus permiting the disposal of bigger heat outputs per unit surface.

Intermediate-lived nuclides affect the mid-section of the curves of thermal loading versus power per borehole. If SF is disposed before they have decayed significantly the rock peak temperature occurs relatively soon, which is when the limit is lower, resulting in a decrease in the allowable thermal power per unit surface. If the disposal is further delayed, the rock peak temperature starts occurring later after emplacement, relaxing the maximum temperature limit and allowing a slightly higher thermal loading. This takes place for ages of SF at disposal approximately from 20 to 40 years. After that range, the remaining radioactive nuclides are very long-lived and the heat source decays slowly, which restricts the permissible thermal loading. The older the SF at disposal, the more "permanent" the heat source becomes, and the lower the allowable heat load per unit surface at the time of emplacement. Notice that if the density of disposal is expressed in Kg of SF per $m^2$, its value will always increase with age of the waste at the time of disposal.

For 12 assemblies per canister and young fuel at disposal, when non-linear VNF temperature restriction takes place, the rock peak temperature occurs very soon after emplacement. The heat source in a single canister is so powerful that the temperature rise at the borehole wall is almost entirely due to the canister in that particular borehole. To avoid the other sources contributing to further increase the rock temperature beyond the maximum permitted, a very large canister pitch would have to be used. A canister pitch larger than 15 m was considered impractical and an additional limit in the form of maximum heat content per canister (minimum age at disposal) was determined in order to avoid that situation. It is important to point out that the maximum thermal loading per canister is not determined strictly by the VNF, but rather by the combination of VNF and NF.

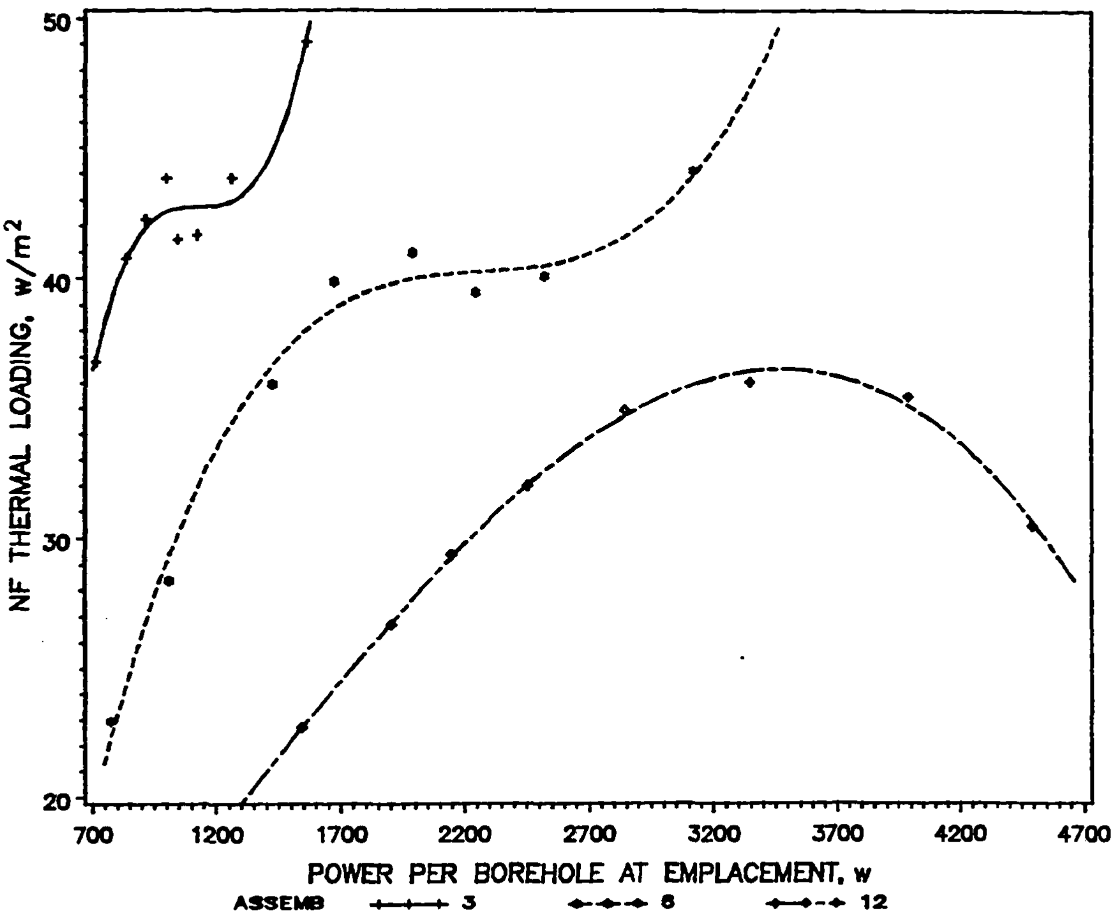
The results for the different rocks are as follows:

- SALT - In all cases the thermal loading allowable by the NF criteria was found to be considerably larger than that allowable by the FF criteria (presented in next section), and there was no need for calculating the thermal loading expression since it never applies.
- GRANITE - Third order polynomials were used for fitting the data, and they are shown in the summary table at the end of the section. The corresponding plots can be seen in Figure 8. Changes in NF thermal loading due to the presence of an air gap, to changes in thermal conductivity and specific heat of the rock, and to increase in the room-to-room distance are also listed in the summary Table 10.
- BASALT - Similarly, a third order polynomial was used to fit the data for each canister design, as can be observed in Figure 9. The polynomials, as well as the numerical results

to variation of the different parameters are given in the summary Table 10.

- TUFF - There are two sets of results for tuff, corresponding to the two repositories mentioned earlier. For the deep repository (high thermal conductivity) the thermal loadings for 3 a/c were very uniform and they were taken as a constant. In this case the minimum acceptable pitch of 1 m plus 1 borehole diameter was reached for relatively young spent fuel, and the analysis for long-delayed disposal was not performed. The NF curves are seen in Figure 10. Three different fits were estimated for the shallower repository (low thermal conductivity), as shown in Figure 11. The numerical results are presented in the summary Table 10.

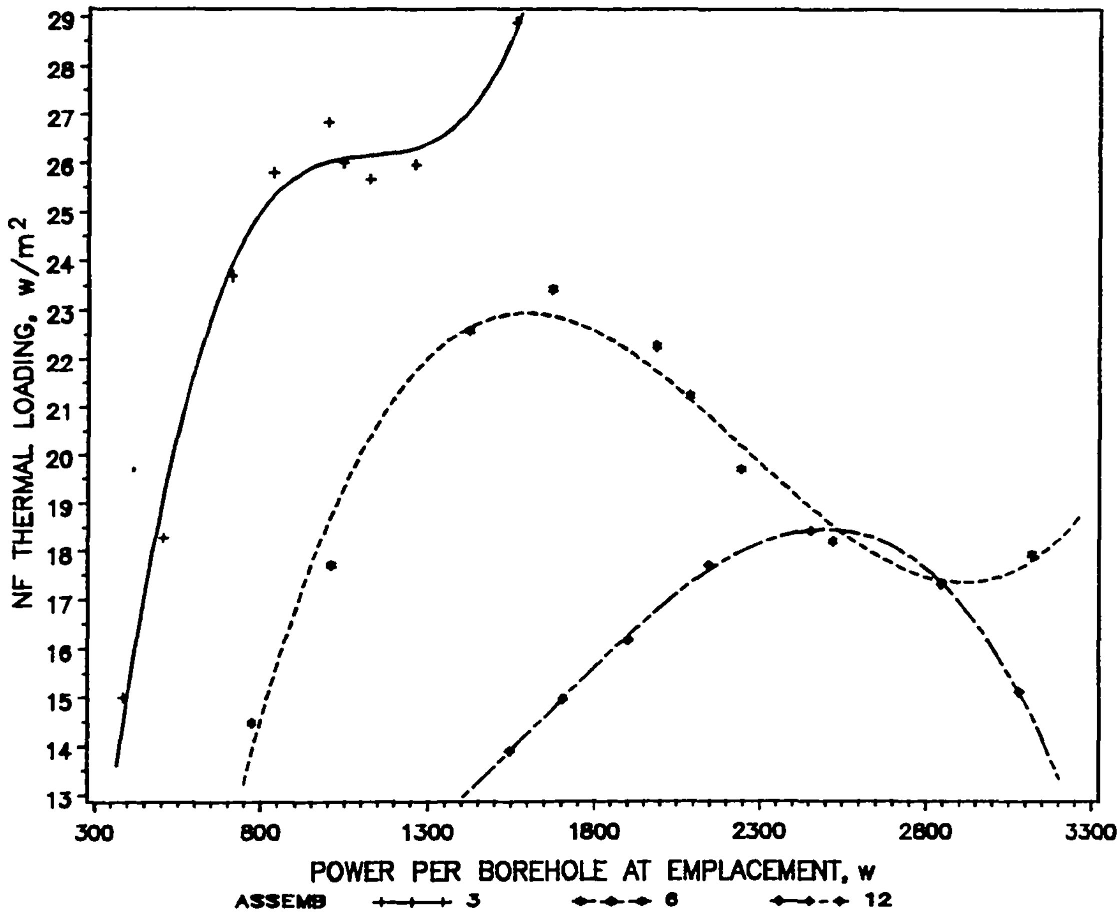
Some general conclusions about the NF thermal loading can be drawn from the numerical values presented. First of all, the presence of an air gap surrounding the SF canister increases the allowable thermal loading, because the temperature restriction at the borehole wall is slightly relaxed, permitting a somewhat smaller canister pitch. Similarly, the air gap allows for a slightly higher power content in the canister at the time of emplacement, an effect that is only noticeable in rocks with low thermal conductivity. The gap effect becomes larger for rocks with smaller thermal conductivity, because in these rocks the peak temperature occurs soon after disposal, which is when the increase in allowable rock temperature due to the gap is larger.




Note: the data points were obtained with the NF model and the lines are the least-squares fits to those points.
The legend indicates to what number of SF assemblies per canister each curve corresponds.

FIGURE 8. Near-Field thermal loading in granite as a function of thermal power per borehole at disposal (SF)

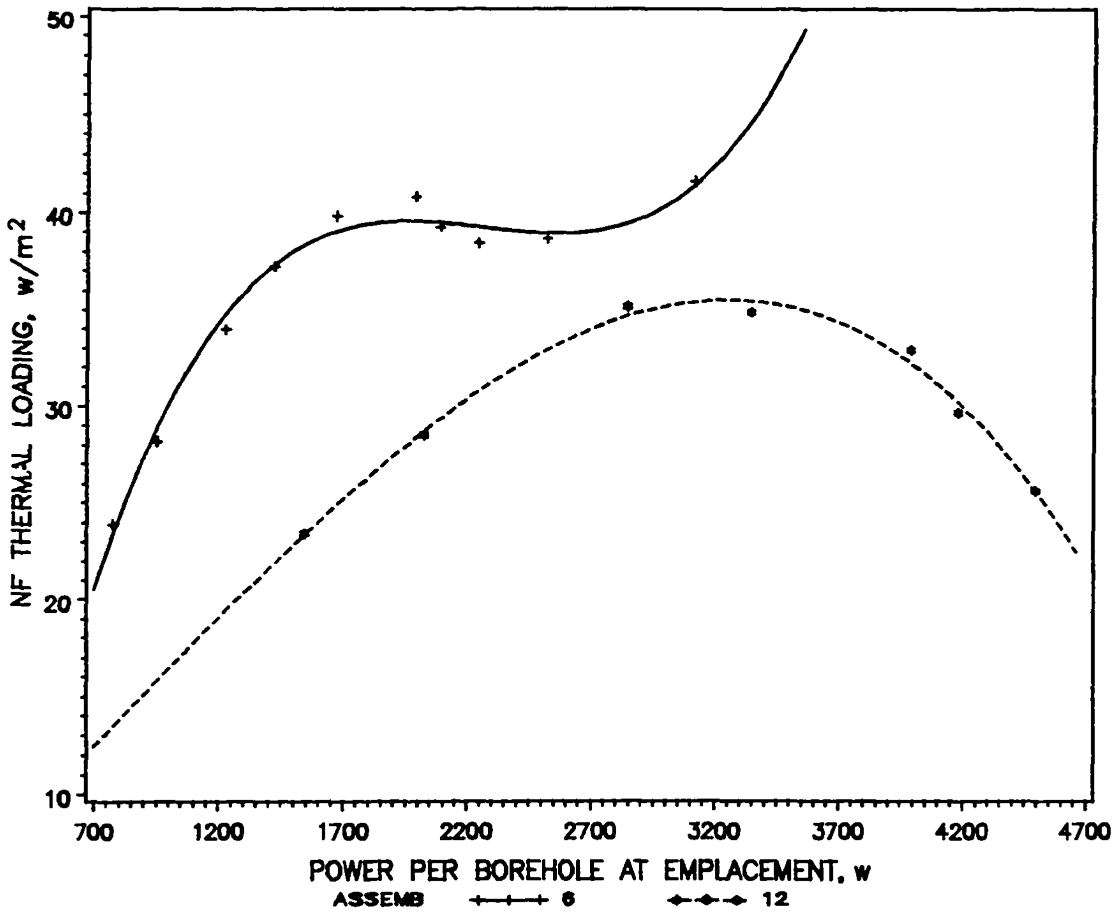
The effect of variations in thermal conductivity with respect to its mean value depend on the sign of the change for rocks with low thermal conductivity. When the rock thermal conductivity is relatively large (granite) small increases in k have an absolute effect similar to




Note: the data points were obtained with the NF model and the lines are the least-squares fits to those points.
The legend indicates to what number of SF assemblies per canister each curve corresponds.

FIGURE 9. Near-Field thermal loading in basalt as a function of thermal power per borehole at disposal (SF)

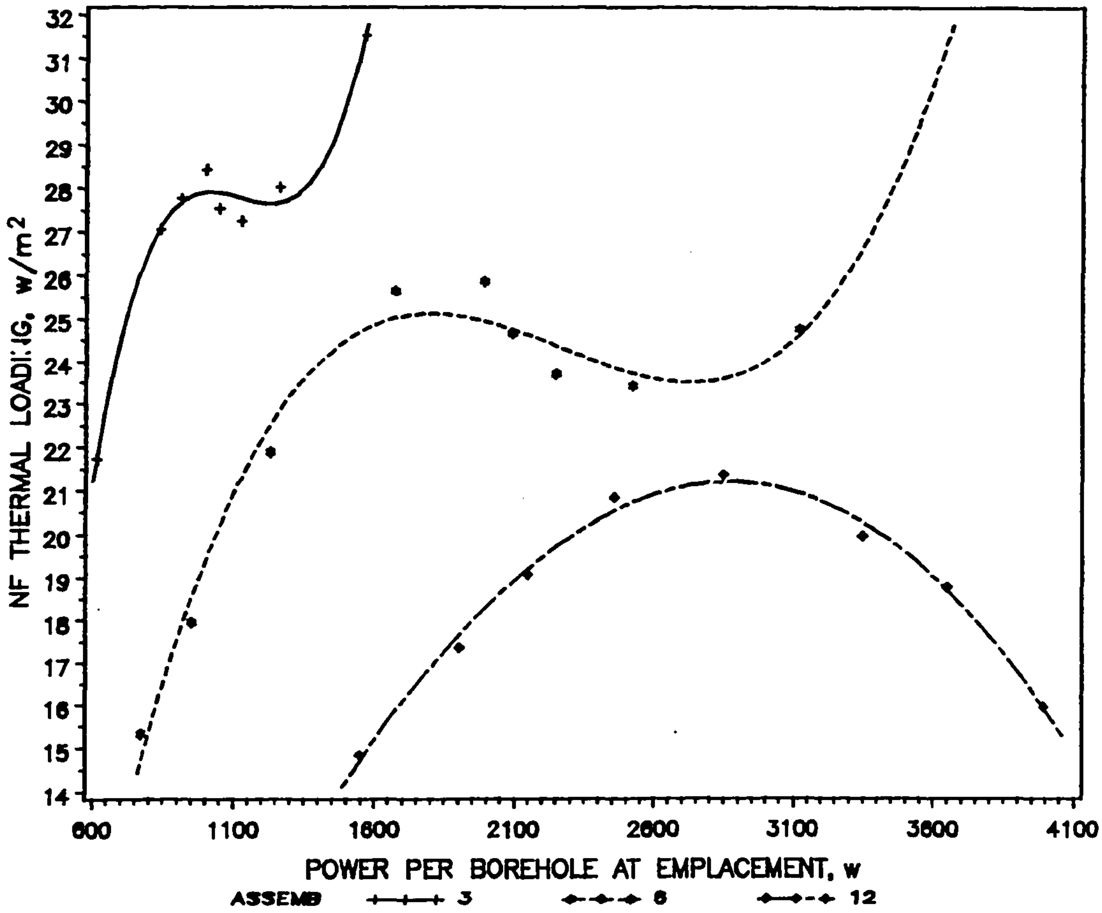
that of small decreases in k. Again, this is caused by the fact that changes in k in low conductivity rocks produce an advance in the timing of the rock peak temperature (negative changes) or a delay (positive changes). When the peak temperature occurs sooner, the limit is more




Note: the data points were obtained with the NF model and the lines are the least-squares fits to those points.
The legend indicates to what number of SF assemblies per canister each curve corresponds.

FIGURE 10. Near-Field thermal loading in deep tuff as a function of thermal power per borehole at disposal (SF)

restrictive, and when it occurs later, it is more relaxed. Therefore, a decrease in k in a low conductivity rock has more impact than an increase in k of the same proportion.




Note: the data points were obtained with the NF model and the lines are the least-squares fits to those points.
The legend indicates to what number of SF assemblies per canister each curve corresponds.

FIGURE 11. Near-Field thermal loading in shallow tuff as a function of thermal power per borehole at disposal (SF)

Changes in specific heat, on the other hand, show a good uniformity, and in general trends they are not dependent upon the canister power at disposal. Similar comments can be made about increasing the room-to-room distance, where the effect is essentially

TABLE 10. Near-field thermal loadings for spent fuel[a]

| Host Rock | a/c | Borehole max. power W | NF allowable thermal loading (w/m²)[c] A | B | C | D | Air Gap Effect (%) | Dr[b] Effect (%) | Change w/Cp (%) | Change w/ρ (%) | Change w/k (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| GRANITE | 3 | | -70.3 | 0.3 | -2.7E-4 | 7.9E-8 | | | | | -5.5 |
| | 6 | | -20.8 | 7.9E-2 | -3.5E-5 | 5.1E-9 | +3 | -0.4(Dr-12) | ±3.9 | | to |
| | 12 | 5100 | -11.3 | 2.9E-2 | -4.9E-6 | 1.3E-10 | | | | | +4.8 |
| BASALT | 3 | | -14.5 | 1.1E-1 | -9.5E-5 | 2.8E-8 | | | | | |
| | 6 | | -21.0 | 6.7E-2 | -3.3E-5 | 4.8E-9 | +3.1 | -0.9(Dr-12) | ±5.7 | ±1.1 | ±9.8 |
| | 12 | 3150 | 17.7 | -1.9E-2 | 1.6E-5 | -3.2E-9 | | | | | |
| TUFF | 3 | | 42.0 | | | | | | | | |
| deep | 6 | | -21.4 | 8.4E-2 | -3.8E-5 | 5.6E-9 | +2.4 | -1.1(Dr-15) | | | |
| | 12 | 5040 | -15.4 | 3.4E-2 | -6.4E-6 | 1.9E-10 | | | | | |
| TUFF | 3 | | -45.5 | 0.2 | -1.8E-4 | 5.4E-8 | | | | | |
| shallow | 6 | | -16.9 | 6.0E-2 | -2.8E-5 | 4.1E-9 | +2.4 | -1.1(Dr-15) | | | |
| | 12 | 4000 | -8.6 | 2.0E-2 | -3.1E-6 | -8.6E-11 | | | | | |

[a]In calculating the changes in NF due to variations in thermal properties, these were allowed to change within the range of one standard deviation.

[b]Dr is the room-to-room distance, expressed in m.

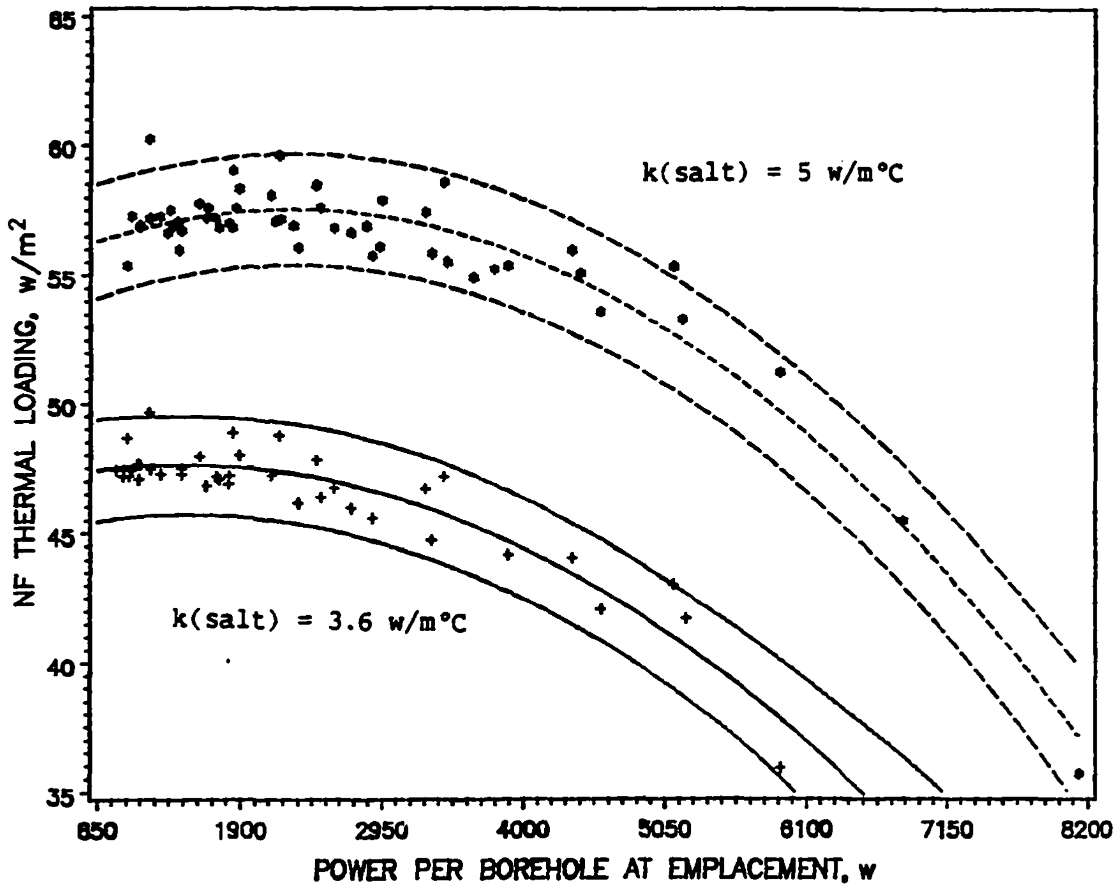
[c]$NF = A + B \cdot Q + C \cdot Q^2 + D \cdot Q^3$, Q expressed in w per borehole.

independent of the canister heat load, but is more significant for low thermal conductivity rocks. Increasing the room-to-room distance does not have as much impact as changing the canister pitch by the same proportion, because the contribution of the heat sources in the same room to the temperature rise at a certain point is bigger than the contribution of sources in other rooms (room-to-room distance is normally larger than the canister pitch). Increasing the distance between rooms by a certain factor does not let the pitch be reduced by the same factor, and consequently, a decrease in the extraction ratio produces a decrease in allowable thermal loading.

b. High-Level waste The behavior of the NF thermal loading with respect to borehole thermal power at disposal shows a more uniform trend for HLW than it did for SF. Because of the virtual absence of long-lived nuclides in HLW, the reduction in thermal loading due to a very slowly decaying heat source for long delayed disposal does not occur in a relevant way. It can be said that for the ages of disposal of interest, from 10 to about 90 years, the allowable NF thermal loading grows with the age at disposal, or in other words, increases when the canister heat load decreases.

Although there are small differences for different canister sizes and concentrations of waste in the glass, they are small enough as to permit a single expression of the thermal loading as a function of the canister power (or thermal power per borehole, which is 3 times larger than the canister power). To give an idea of the order of these differences, 95 % confidence intervals have been plotted along with the least squares estimates of the thermal loadings. It must be pointed out that for disposal of very hot waste (10 to 12 years of age at disposal) an increase in the allowable thermal loading was again observed, although it was not as important as in the case of SF. Because this only took place in a very small power range, and as a conservative approach, the corresponding data points were not included in the least squares estimates.

- SALT - In the case of HLW the NF thermal loading is sometimes more restrictive than the FF, so the NF function has been calculated; its plot is shown in Figure 12 and its numerical values are summarized in Table 11. Notice that there are two different estimates, one for the case of high conductivity and another for low conductivity. Because of the large difference in NF loadings between these cases, two different fits were performed instead of evaluating an uncertainty band for a mean value.
- GRANITE - The results for granite are shown in Figure 13 and the corresponding entries in the summary table. The effect of the different parameters on the NF loading is given in the form of an error band around the mean value.
- BASALT - This being a rock with low thermal conductivity showed a larger difference between thermal loadings for varying canister size and waste concentration. The differences were not as considerable as they were in SF, and a common expression for the thermal loading still seemed

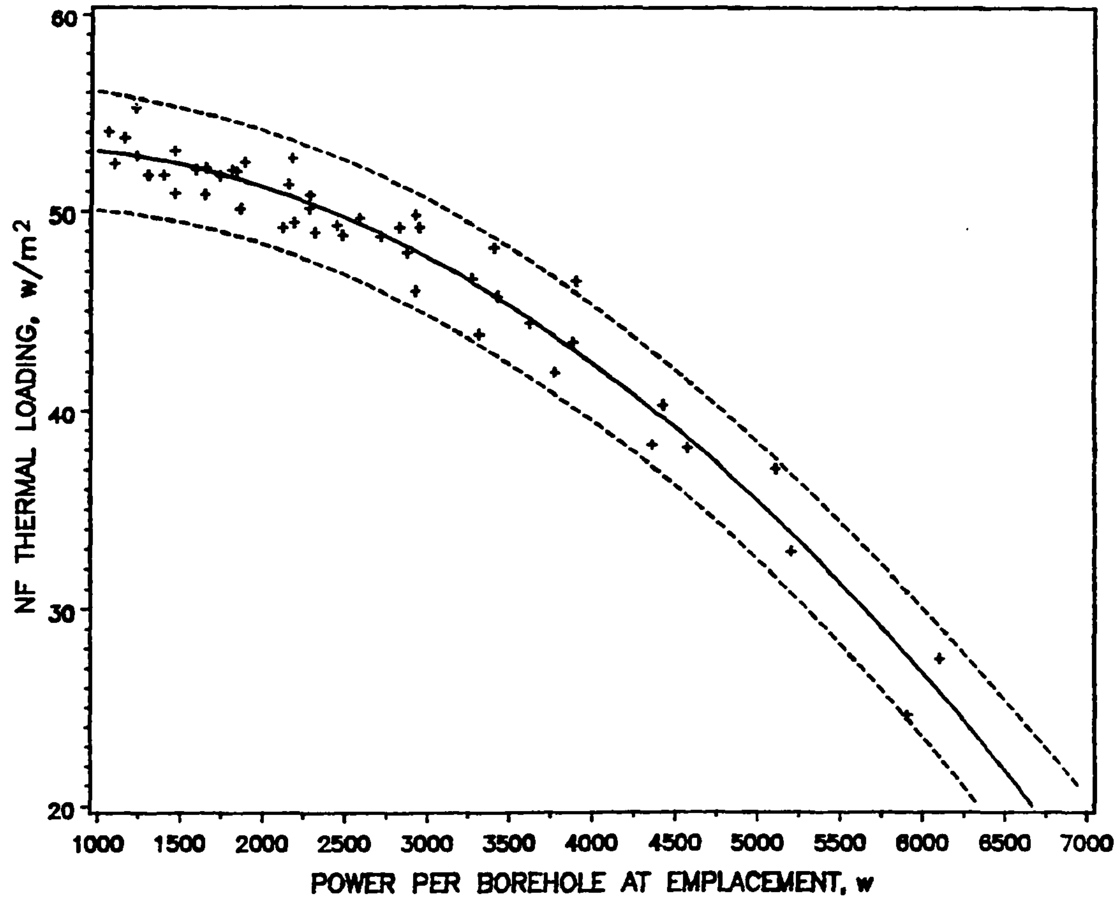



Note: the data points were obtained with the NF model and the lines are least-squares fits to those points (with 95% confidence intervals).

FIGURE 12. Near-Field thermal loading in salt as a function of thermal power per borehole at disposal (HLW)

reasonable. The plot of the function is shown in Figure 14 and the numerical values are in Table 11.

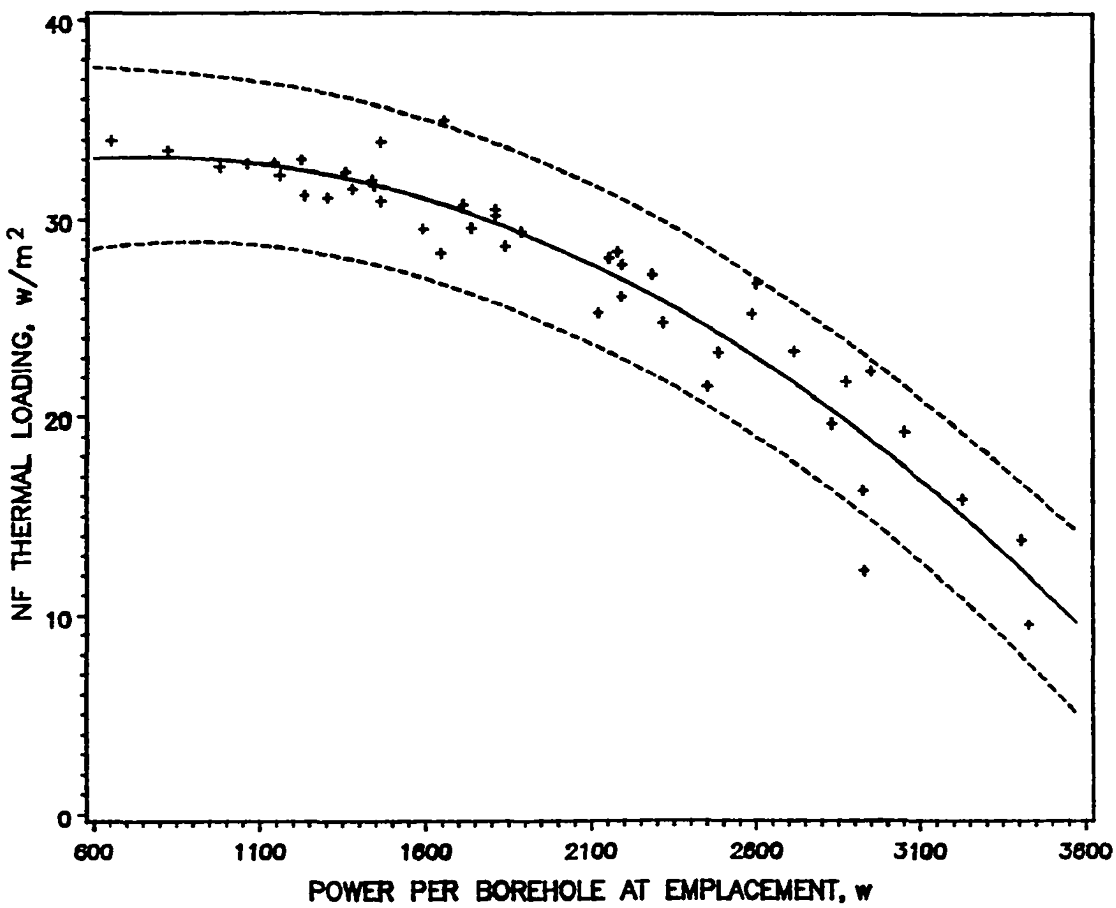
- TUFF - The allowable thermal loadings for the two different repositories definitely show an important difference, and they were analyzed independently. Results are listed in the summary Table and the plots are shown in Figure 15.




Note: the data points were obtained with the NF model and the lines are least-squares fits to those points (with 95% confidence intervals).

FIGURE 13. Near-Field thermal loading in granite as a function of power per borehole at disposal (HLW)

The principal conclusions from the NF thermal analysis for HLW disposal are qualitatively similar to those drawn for SF disposal, although the numerical values differ, considerably in some cases. The air gap again shows a tendency to increase the allowable thermal loading, more so for rocks with low thermal conductivity and for high canister heat contents. Increasing the room-to-room distance makes the

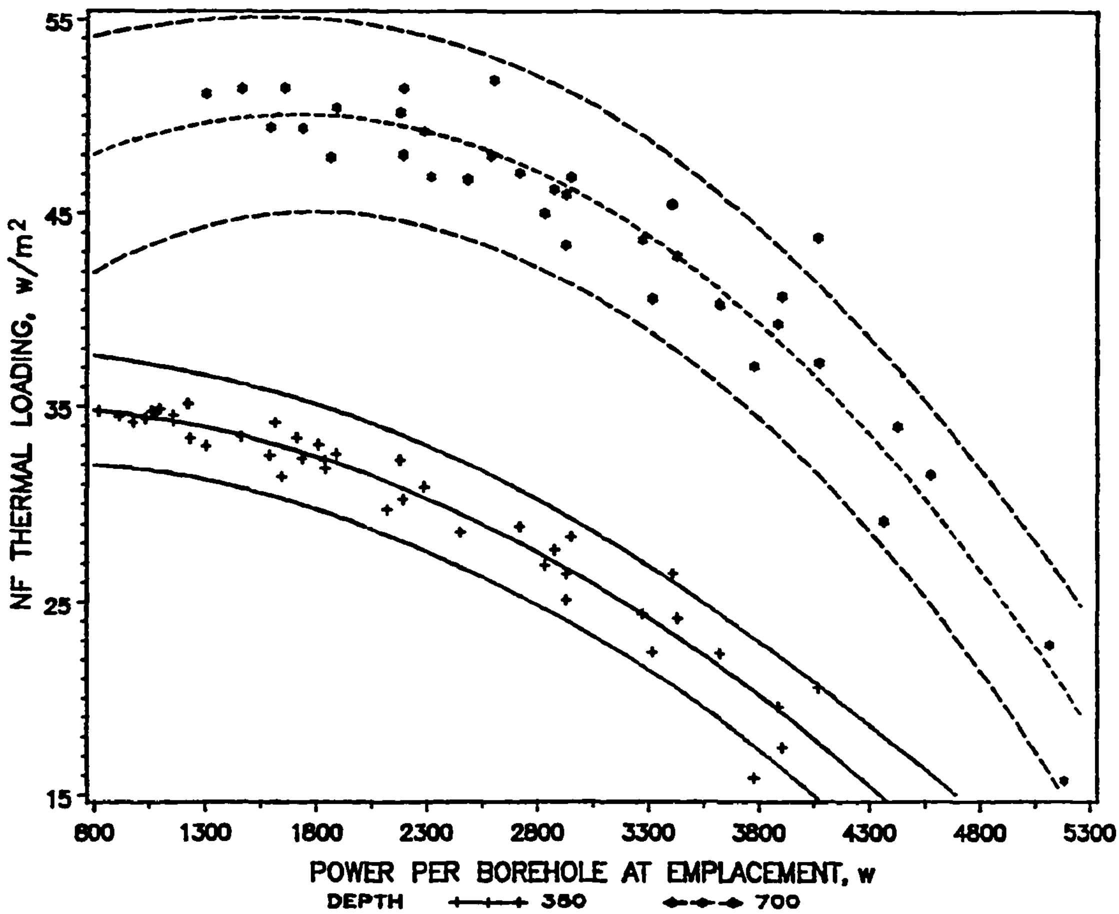



Note: the data points were obtained with the NF model and the lines are the least-squares fits to those points (with 95% confidence intervals).

FIGURE 14. Near-Field thermal loading in basalt as a function of power per borehole at disposal (HLW)

thermal loading decrease, an effect that becomes less and less important for higher rock thermal conductivities.

Variations in thermal conductivity show again the importance of the direction in which these variations take place with respect to the mean value. More drastic changes occur when the thermal conductivity decreases by a certain percentage than by increasing it by the same




Note: the data points were obtained with the NF model and the lines are least-squares fits to those points (with 95% confidence intervals).

FIGURE 15. Near-Field thermal loading in tuff as a function of power per borehole at disposal (HLW)

amount. Uniform responses are seen for changes in specific heat and density values of the host rock.

### 3. Far-Field results

The maximum allowable thermal loadings to satisfy the FF criteria were found for both SF and HLW disposal in the four possible rocks.

TABLE 11. Near-Field thermal loadings for HLW[a]

| Host Rock | Borehole max. power w | NF allowable thermal loading $(w/m^2)$[c] A | B | C | Air Gap Effect (%) | Dr[b] Effect (%) | Change w/Cp (%) | Change w/$\rho$ (%) | Change w/k (%) |
|---|---|---|---|---|---|---|---|---|---|
| SALT (k=5) | 8100 | 54.4 | 2.7E-3 | -5.9E-7 | +0.8 | -0.5(Dr-12) | ±0.7 | | |
| SALT (k=3.6) | 6100 | 46.5 | 1.5E-3 | -5.0E-7 | +0.8 | -0.5(Dr-12) | ±0.7 | | |
| GRANITE | 6000 | 52.5 | 1.2E-3 | -9.1E-7 | +2.3 | -1.1(Dr-12) | ±0.5 | | -6.6/+4.9 |
| BASALT | 3100 | 31.4 | 4.5E-3 | -2.9E-6 | +3.2 | -1.2(Dr-12) | ±5.9 | ±0.9 | ±12 |
| TUFF (deep) | 5100 | 42.8 | 8.4E-3 | -2.5E-6 | +2.4 | -1.5(Dr-15) | | | |
| TUFF (shallow) | 5100 | 34.8 | 9.2E-4 | -1.3E-6 | +2.4 | -1.5(Dr-15) | | | |

[a] In calculating the NF changes due to variations in thermal properties, these were allowed to change within the range of one standard deviation.

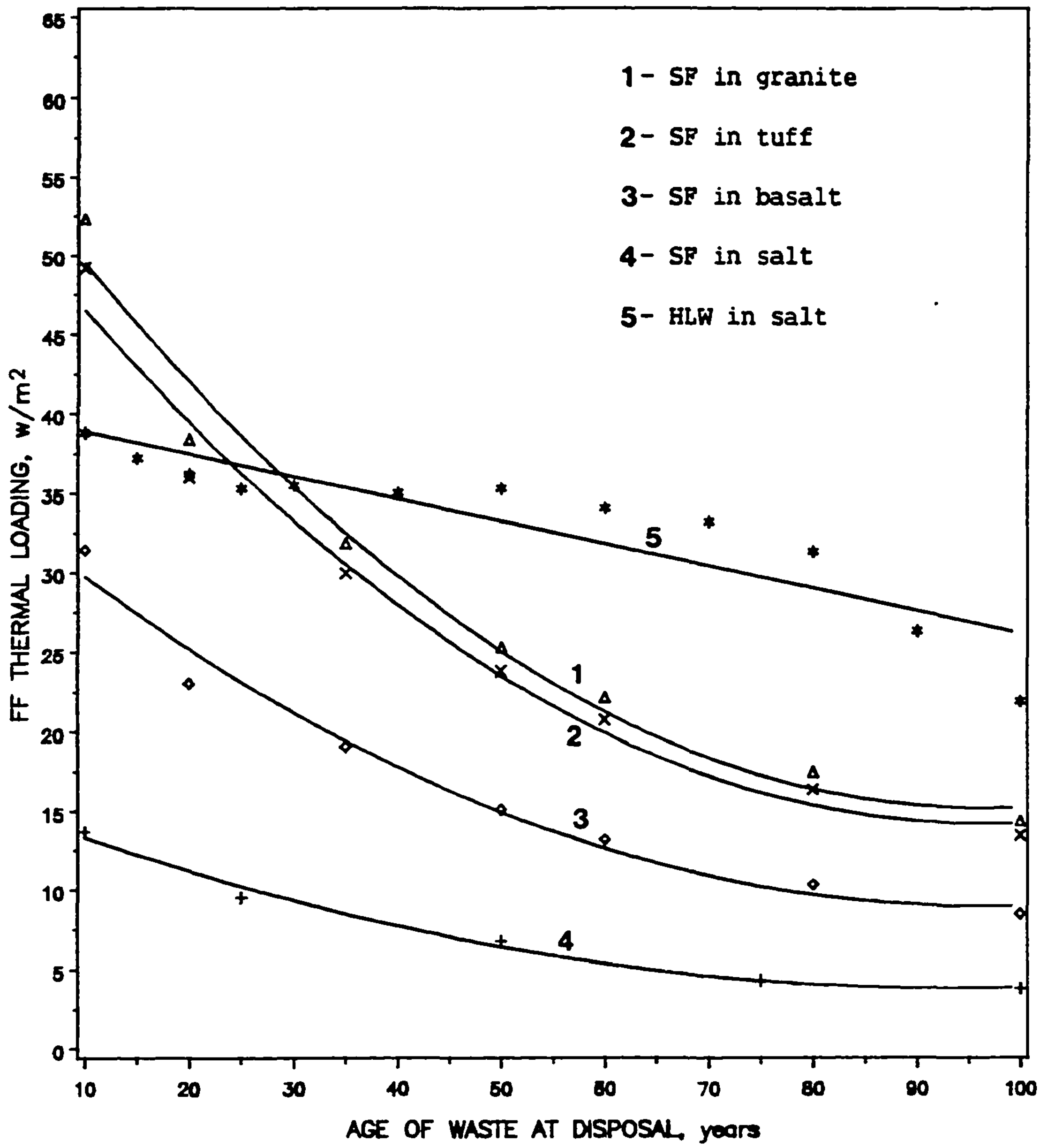
[b] Dr is the room-to-room distance in m.

[c] $NF = A + B \cdot Q + C \cdot Q^2$, Q expressed in w per borehole.

For disposal of HLW in granite, basalt and tuff, the FF loading was always about an order of magnitude larger than the NF, and never was restrictive for ages at disposal ranging from 10 to 100 years. Because of this, the FF numerical results for these three cases are not presented in this section.

In the Far-Field model the entire repository is treated as a slab heat source, and some of the parameters upon which the NF loading depended are no longer important. Such is the case of the canister size, waste concentration, and room-to-room distance. The significant parameters in the FF are the rock thermal properties, the coefficient of thermal expansion in particular, the depth of the repository and the age of the waste at disposal. The thermal power per borehole, so convenient in expressing the results of the Near-Field, cannot be used for the same purpose in the Far-Field. Instead, the FF allowable thermal loadings are expressed as a function of the age at disposal. In Figure 16, the thermal loading is expressed in $w/m^2$, useful for comparing with the NF loading.

The behavior of the maximum allowable FF thermal loading with respect to the age of the waste at disposal is again expressed in the form of a least-squares fit for each of the rocks and waste forms considered. A second order polynomial has been used in all cases. The numerical results of these fits are given in Table 12, along with the variations in FF produced by changing the depth of the repository and the rock thermal properties. In calculating the mean value of the FF thermal loading, as given in the Table and plotted in Figure 16, the




Note: the data points were obtained with the FF model and the lines are the least-squares fits to those points.

FIGURE 16. Far-Field thermal loading versus age at disposal

mean values of the rock thermal properties were used (Section C). The baseline depths were selected according to the most likely choice of repositories in each rock:

- SALT - 750 m, Deaf Smith Co., Palo Duro Basin, Texas.
- GRANITE - 750 m. (No possible repository location in this medium has yet been proposed).
- BASALT - 1000 m, Columbia Plateau.
- TUFF 1 - 350 m. (Paintbrush formation, Yucca Mountain, Nevada).
- TUFF 2 - 700 m. (Bullfrog formation, Yucca Mountain, Nevada).

Although two different cases were studied for disposal in tuff, the FF thermal (and mass) loadings turned out to be very similar. An increase in the depth of the repository results in a decrease in the permissible thermal loading, but in the case of tuff, there is also a substantial increase of thermal conductivity and specific heat when going from the shallow repository to the deeper one. The effect of increasing the depth is almost entirely compensated by the increase in thermal properties and the differences in calculated FF loadings between the two cases were found to be smaller than 3 %, in favor of the shallow site. Only the latter is plotted in the figure.

The effect of the depth on the FF thermal loading is expressed in the table in absolute variation of the loading for absolute changes in the depth with respect to the baseline case. Because the repository depth is one of the parameters analyzed in the economic model, this form is more appropriate than defining a percentage range about a mean

TABLE 12. Far-Field thermal loading results

| Host Rock | Waste form | FF allowable thermal loading ($w/m^2$)[a] A | B | C | Change with depth[b] ($w/m^2$) | Change $w/\rho$ (%) | Change w/k (%) | Change $w/\alpha$ (%) | Change w/Cp (%) |
|---|---|---|---|---|---|---|---|---|---|
| SALT | HLW | 35.9 | 8.8E-1 | -2.1E-3 | 0.6(600-H) | | | | |
| SALT | SF | 14.6 | -2.1E-1 | 1.1E-3 | 0.6(600-H) | | | | |
| GRANITE | SF | 52.5 | -7.8E-1 | 4.0E-3 | 2.5(600-H) | | ±2.9 | ±16.7 | ±4.5 |
| BASALT | SF | 33.6 | -5.1E-1 | 2.6E-3 | 1.8(1000-H) | | ±4.8 | ±18.3 | ±8.1 |
| TUFF 700 m | SF | 54.8 | -8.2E-1 | 4.2E-3 | | ±4.7 | ±5.9 | ±14.2 | ±4.5 |
| TUFF 350 m | SF | 55.8 | -8.3E-1 | 4.3E-3 | | ±4.7 | ±5.9 | ±14.2 | ±4.5 |

[a] $FF = A + B \cdot A + C \cdot A^2$, where A, the age of waste at disposal is expressed in years.

[b] H is the depth of the repository in m.

value.

Changes in the FF loading with variations in thermal properties are expressed in the form of an error band about the mean value. A range of one standard deviation in the thermal properties was used to calculate the uncertainty band. No entry is made in the table for negligible changes in FF with thermal properties nor for negligible changes in the properties.

The coefficient of thermal expansion is the parameter that produces the larger variations in the FF thermal loading, as could be expected from the fact that the factor limiting the loading is the maximum surface uplift, directly proportional to $\alpha$. A significant change in the repository depth would also result in an important change in the thermal loading.

An additional plot, Figure 17, in which the FF loading is given in the form of a mass loading, in $Kg/m^2$, is also included. The choice of this variable results appropriate for the discussion of the FF and the comparison of SF and HLW disposal.

Figure 17 shows that the mass loading keeps increasing with the age of the waste at disposal, which was not true when the FF was expressed as a thermal loading. That indicates that by aging the waste the density of disposal does increase, resulting in a smaller repository area. The difference in the FF loading between SF and HLW disposal can be better realized when the FF is expressed as a mass loading. For any host medium, the permissible mass loading is about one order of magnitude larger for HLW. Recall that the mass of HLW is

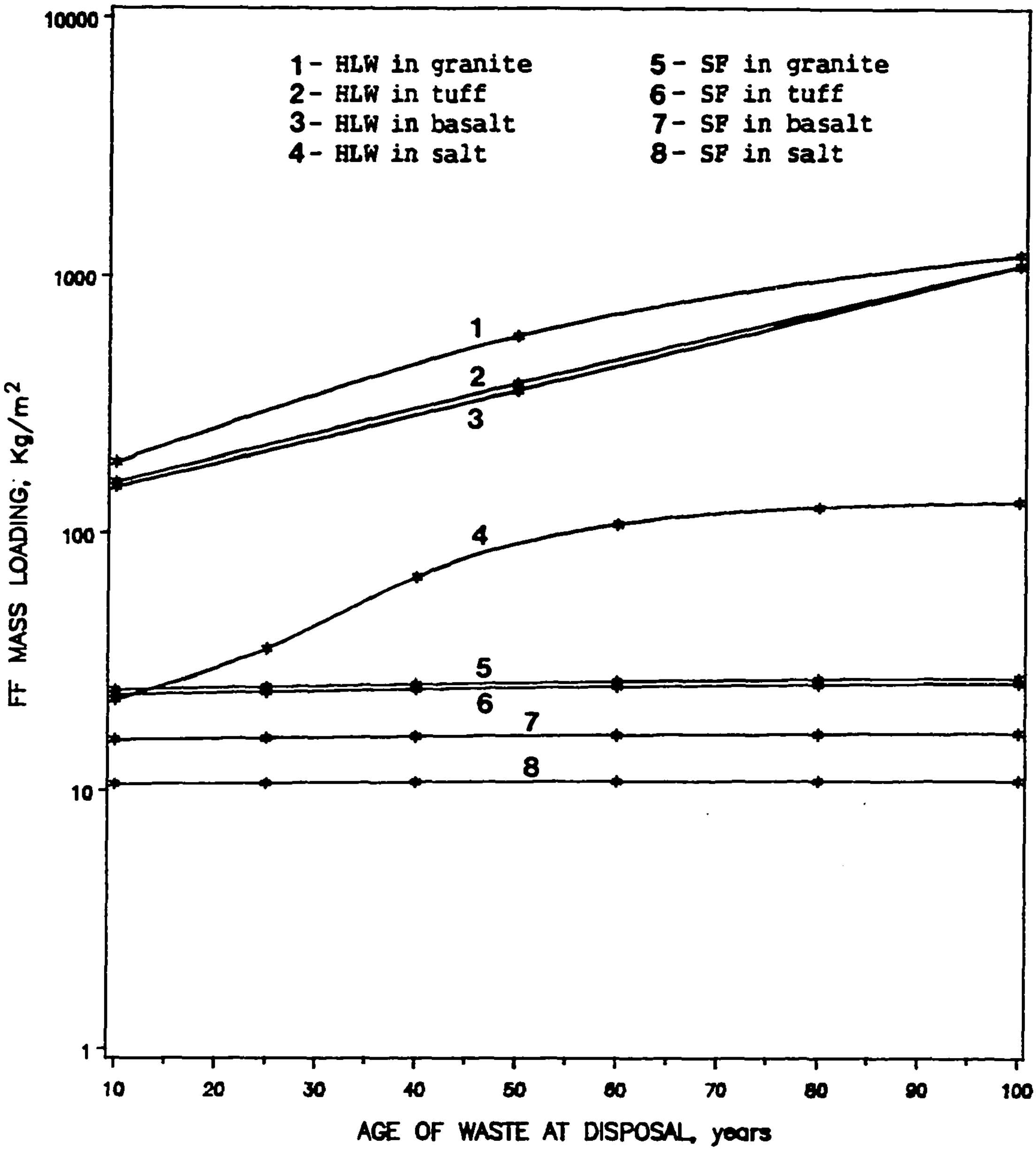



FIGURE 17. Far-Field mass loading versus age at disposal

expressed in equivalent mass of spent fuel from which the high-level waste was generated. The reason for this behavior is the difference in heat generation per MTHM, larger in spent fuel, and the faster decaying source in high-level waste. The fact that the heat source in spent fuel decays slowly also accounts for the small change in mass loading for ages at disposal ranging from 10 to 100 years. The curve of mass loading versus age at disposal is steeper for HLW disposal, thus offering the possibility of bigger reductions in excavation requirements by aging the waste.

### 4. Summary of results

For each scenario considered in the economic analysis the excavation requirements are evaluated. For that purpose, the results of the thermal analysis are incorporated into the economic model in the same way as they are presented in the preceding sections for NF and FF loadings. The loadings under the two criteria are evaluated separately and the more restrictive of the two is applied in calculating the final loading and the corresponding excavation requirements. In this section, however, the combination of the Near-Field (including the VNF) and the Far-Field is presented in order to compare the different cases under the thermal criteria.

In merging the results of the NF and the FF, the age of the waste at disposal has been chosen as the common independent variable, whereas the mass loading has been selected as the dependent one for its simplicity in plots. Only the cases where, within the range of ages at disposal of interest, there was a shift in the limiting field (from NF to FF) are plotted in the set of figures presented below.

The results of combining the different thermal fields, for each rock type can be summarized as follows:

- SALT - The far-field is always more restrictive than the near-field within the range of interest for both HLW and SF, except for the case of a 50 cm ID canister with 20 w/o waste concentration, where the NF dominates for ages at disposal from 10 to 13 years. Although salt is the rock with the larger thermal conductivity and the permissible NF loadings were found to be better than in any other medium, its coefficient of thermal expansion is almost one order of magnitude larger than that of other rocks, resulting in a very limiting FF permissible loading, which makes salt the rock with the poorest allowable density of disposal.
- GRANITE - For HLW disposal the Far-Field never becomes restrictive, and the mass and thermal loadings are determined by the NF. There are two ranges of disposal ages, however, for spent fuel; one in which the NF limits the loading (younger waste) and a second, for older waste, where the FF criteria become the limit. The age for which the switch occurs depends upon the number of assemblies per canister. For 12 a/c there is an additional restriction for very young spent fuel, which is the maximum power per borehole. For heavily loaded canisters (12 a/c) disposal cannot take place

before a certain age, until the power per canister is below the maximum acceptable. The plots of the combined mass loadings are shown in Figures 18, 19, and 20, for 3, 6 and 12 assemblies per canister respectively.

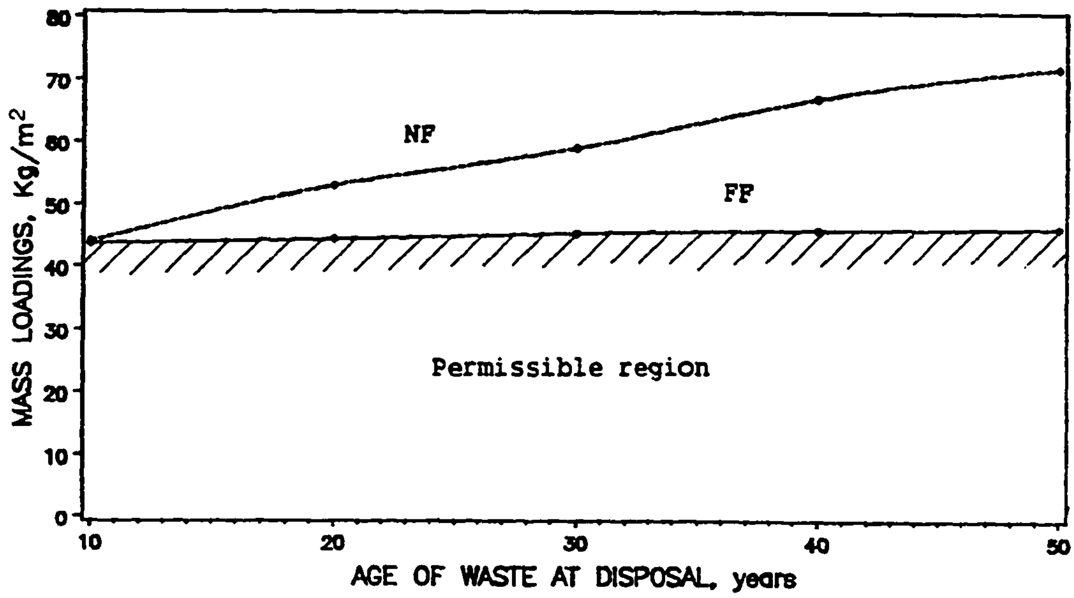



FIGURE 18. SF mass loading vs. age at disposal in granite, 3 a/c

- BASALT - As in the case of granite, the Near-Field criteria always restrict the density of disposal for HLW. For SF disposal, there is a disposal age where the limiting criteria changes from one field to the other, and is a function of the canister content. A minimum disposal age requirement is only necessary for canisters containing 12 assemblies. Figures 21, 22, and 23 show the combined permissible mass loadings for the three possible canister sizes.

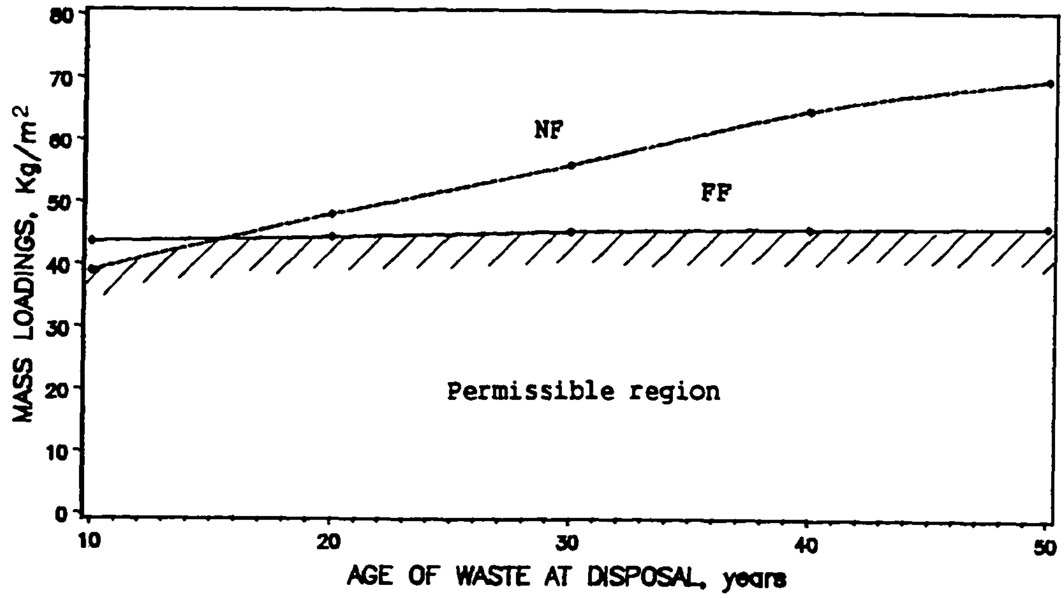



FIGURE 19. SF mass loading vs. age at disposal in granite, 6 a/c

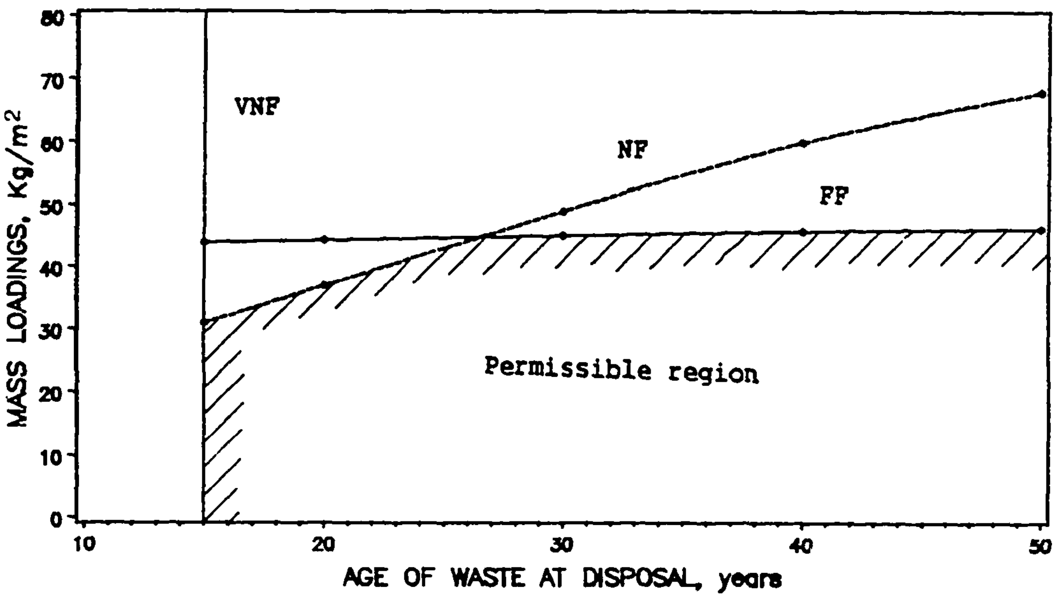



FIGURE 20. SF mass loading vs. age at disposal in granite, 12 a/c

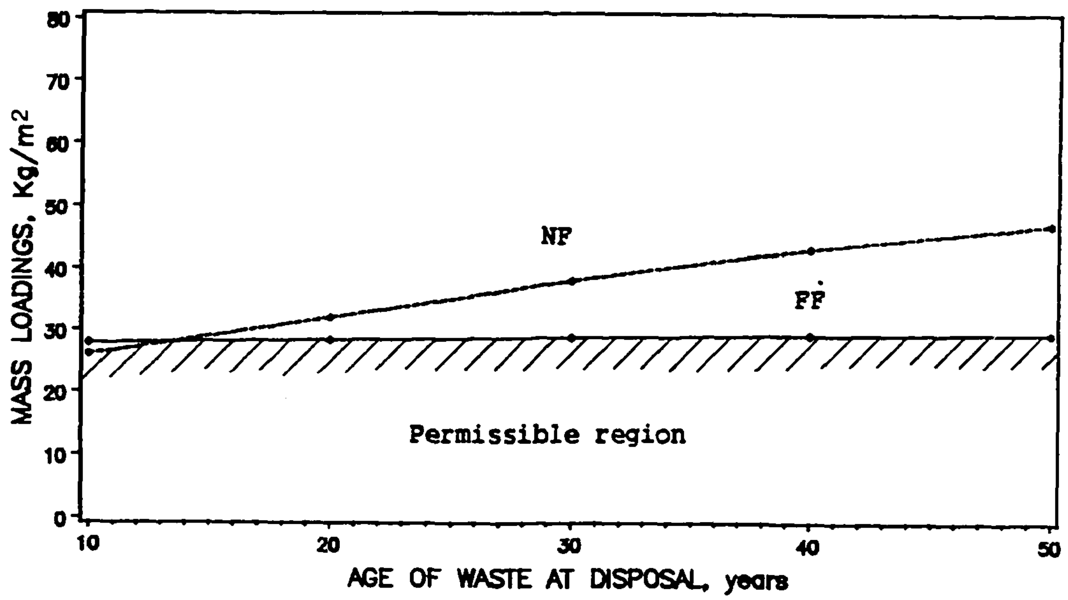



FIGURE 21. SF mass loading vs. age at disposal in basalt, 3a/c

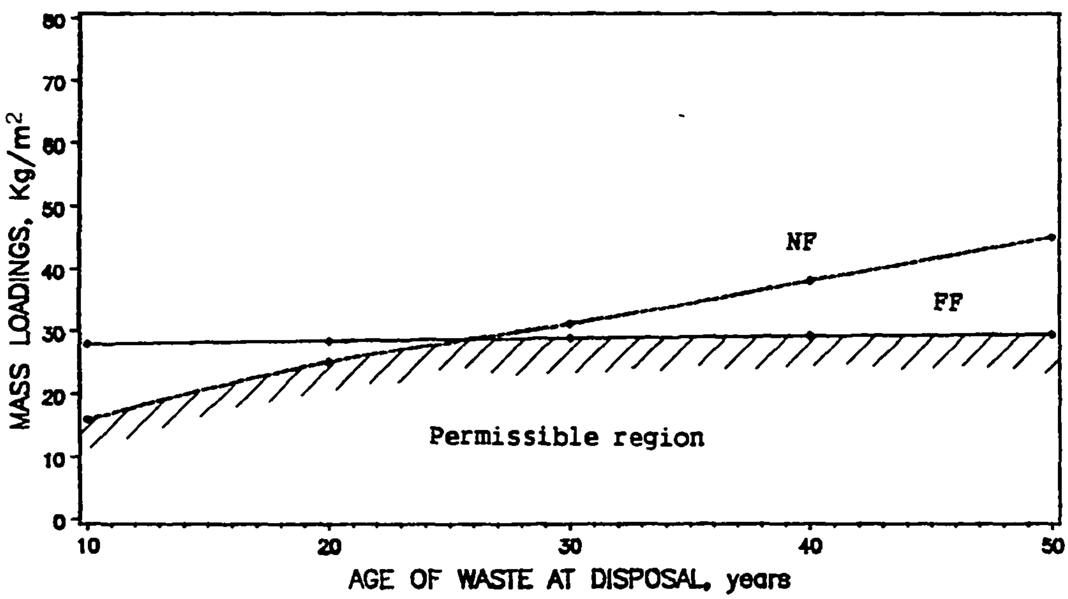



FIGURE 22. SF mass loading vs. age at disposal in basalt, 6a/c

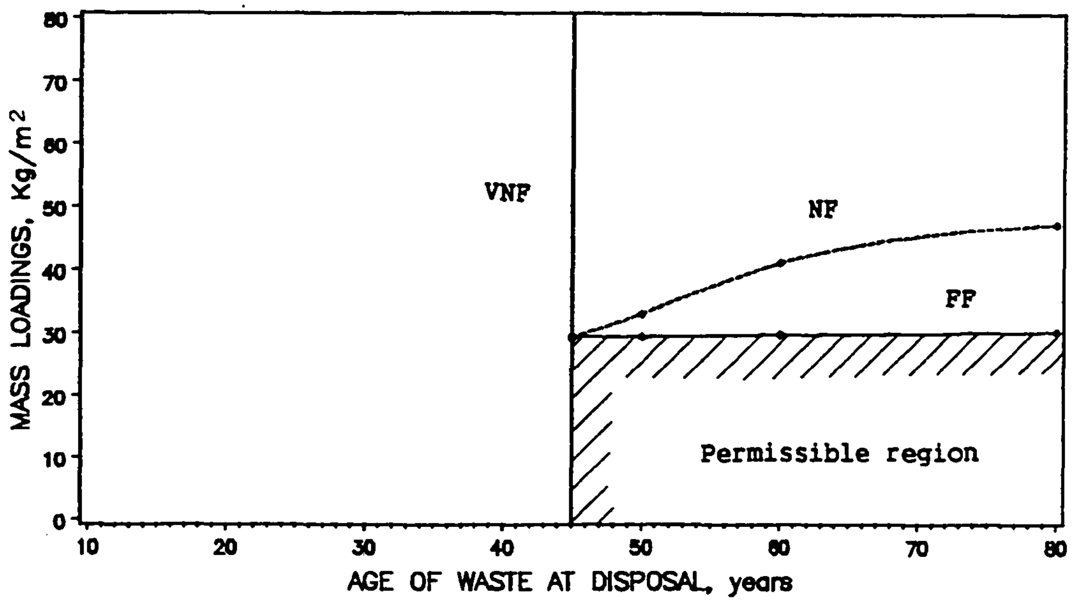



FIGURE 23. SF mass loading vs. age at disposal in basalt, 12 a/c

- TUFF - NF is the limiting criteria for HLW, for both proposed repository locations (350 and 700 m). For SF disposal, it is necessary to make a distinction between the two repository depths. In the shallow repository case, the permissible loadings according to the NF criteria are very similar in magnitude to those of the FF criteria, these being a little larger over the range of interest of disposal ages. Hence, in the 350 m deep repository in tuff, only the NF thermal loadings will determine the density of disposal. At 700 m, however, there is again a range of ages where the FF dominates, and another range where the limit is the NF, the particular magnitude of these ranges depending upon the number of assemblies per canister. The three cases for the deep repository in tuff are displayed in Figures 24, 25, and 26.

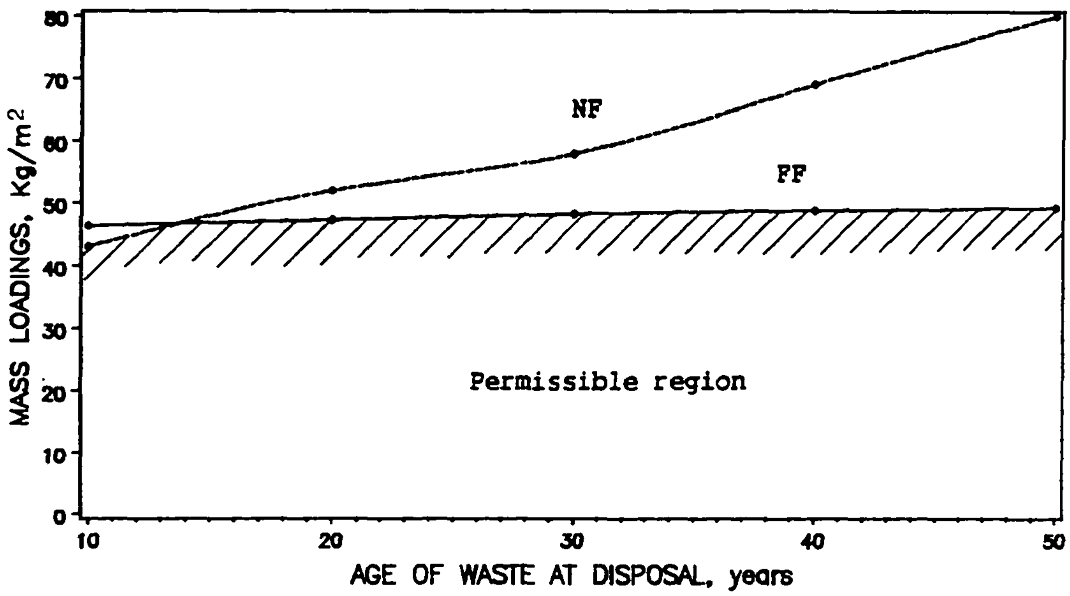



FIGURE 24. SF mass loading vs. age at disposal in deep tuff, 3a/c

A set of qualitative conclusions can be drawn from overall results of the thermal analysis. First of all, when comparing the thermal (or mass) loadings for the two waste forms, the results clearly indicate that, for each rock formation, a higher density of disposal can be permitted for high-level waste. If the delay of disposal is the same, a larger repository would be needed for spent fuel than for high-level waste. Among the four rocks considered, salt (regardless of its better NF acceptable loadings) is the repository medium that would require the largest excavation area. In particular, the density of disposal of SF in salt is at least one order of magnitude smaller than disposal in any

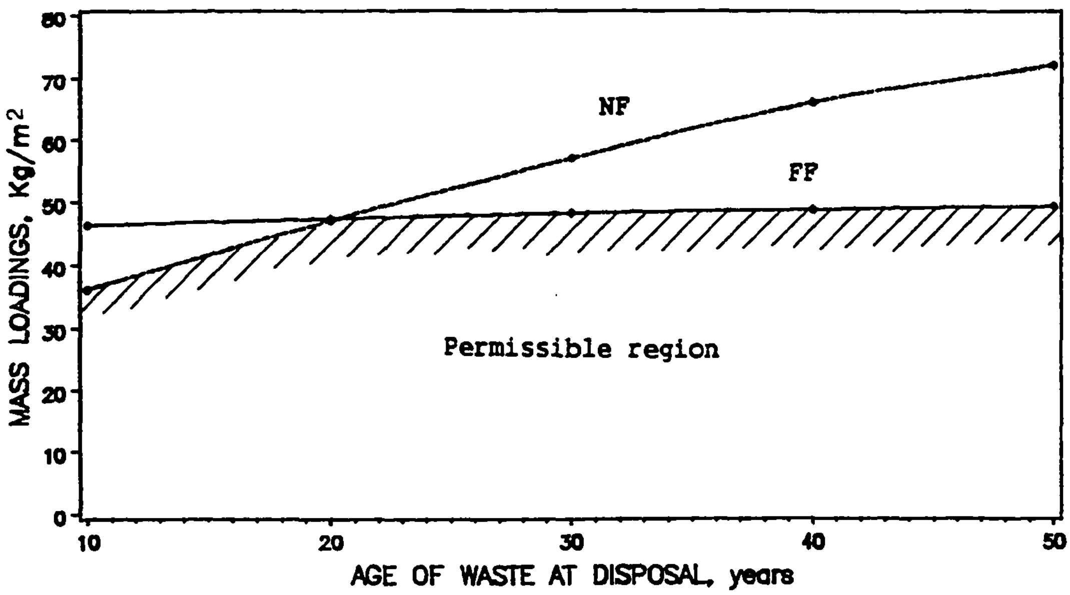



FIGURE 25. SF mass loading vs. age at disposal in deep tuff, 6 a/c

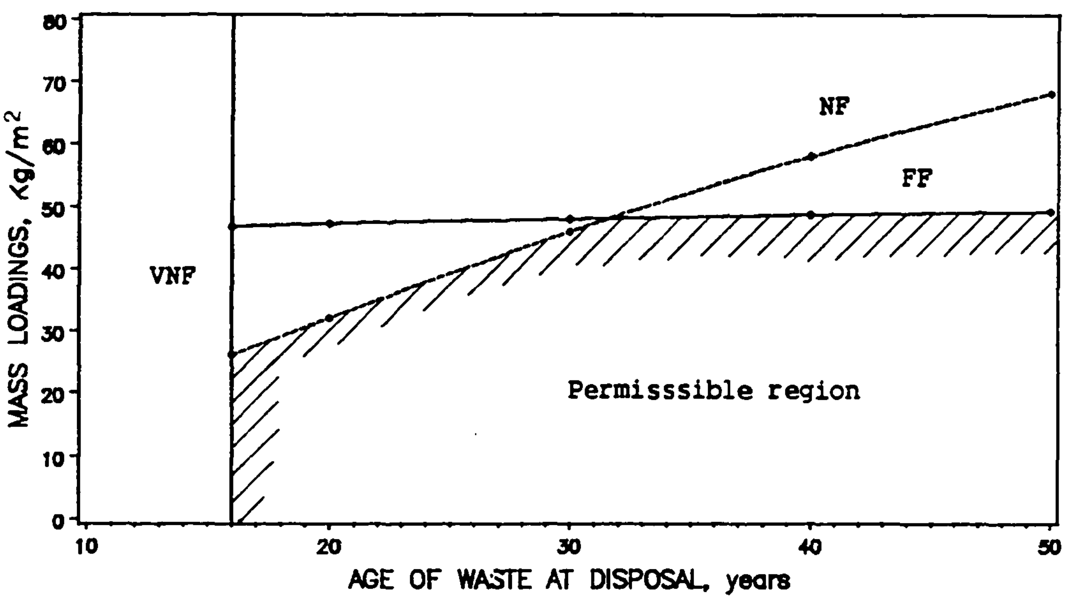



FIGURE 26. SF mass loading vs. age at disposal in deep tuff, 12 a/c

other rock formation or disposal of HLW.

For disposal of HLW in granite, basalt, and tuff formations, the thermal loadings are always dictated by the Near-Field criteria. Granite has the higher permissible loadings and basalt, because of its low thermal conductivity, accepts the smaller loadings. Tuff is the rock that presents the larger uncertainty because of the considerable differences in thermal properties between the two possible repository horizons. In the case of SF disposal in these three rocks, the limit in disposal densities changes from the NF to the FF criteria, depending on the delay of disposal. The exception to this rule is disposal in shallow tuff, in which case the NF is dominant for ages of disposal from 10 to 100 years. The more restricted loadings appear in the disposal of canisters containing 12 assemblies of SF, where a minimum cooling time before disposal of more than 10 years is required in order to let the total heat output per borehole decay to a permissible level (given by a combination of NF and VNF criteria). The minimum cooling time in those cases depends upon the thermal conductivity of the host rock, such that the lower the conductivity the longer the required cooling time. In the disposal of canisters with 3 or 6 assemblies, there is no difference in the permissible density of disposal once the FF is the dominant factor. Before that, when the NF loading is the limit, the loadings for the 6 a/c cases are slightly more restricted.

Considering only the results of the thermal analysis, disposal of HLW in granite would appear to be the optimum situation. If spent fuel is to be disposed instead, granite is again the preferred medium, and canisters containing 6 assemblies would be desirable for ages of disposal when the FF limits the density of disposal. For younger SF at disposal, where the NF is more restrictive than the FF, 3 assemblies per canister might be better. Naturally, these considerations are only from the thermal analysis point of view. Because of varying storage costs for different delays of disposal and different excavation costs in different media, only the economic analyis can really provide information about the preferred rock, waste form, and canister size.

# V. ECONOMIC ANALYSIS MODEL

The economic model has been prepared so that the costs are evaluated in 1987 dollars and can be discounted with respect to the year 1998, when the operations in the MRS facility are scheduled to start. Because the possibility of delays of disposal operations after the year 2003 is contemplated in the economic analysis, the year 2003 is not a good reference for the discounting of costs. The optional actual discount rate (after subtraction of inflation) can be selected as one of the inputs to the model. Costs can be estimated for any of the three cycles described in the previous chapter and for any of the alternative scenarios. The total system costs are broken down into 5 main categories:

- Spent fuel transportation costs to the MRS, assumed by the utilities but estimated in the economic analysis for analyzing the net effect of possible MRS locations.
- Storage costs, which include the facility construction costs and operations, with optional consolidation of the SF assemblies.
- SF transportation from the MRS to the repository, only applicable if the MRS facility is not co-located with the repository.
- Packaging facility, located at the disposal site, and including the overpacking costs, possible waste receiving/handling operations and optional consolidation of the spent fuel assemblies.

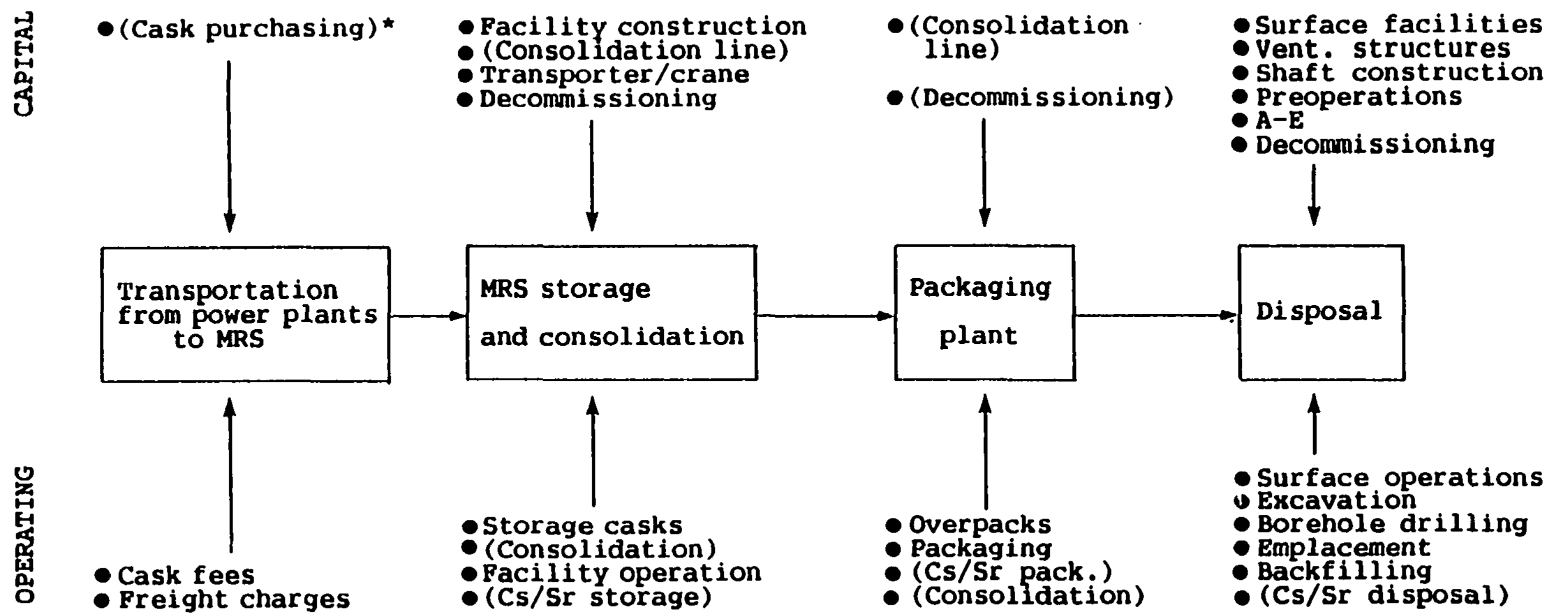
- Disposal costs, including the repository surface facilities and operations (with the exception of storage and packaging), the shaft construction and operations, and the totality of the underground developments and operations.

Two general cases showing the different cost components in each of the categories are shown in Figures 27 and 28, the first for a scenario with the MRS facility co-located with the repository and the second for the MRS facility located in Tennessee. The costs involved in each of the categories are discussed in the following sections. The procedure to estimate the different unit or baseline cost for each component is explained in detail in Appendix C.

## A. Transportation Costs

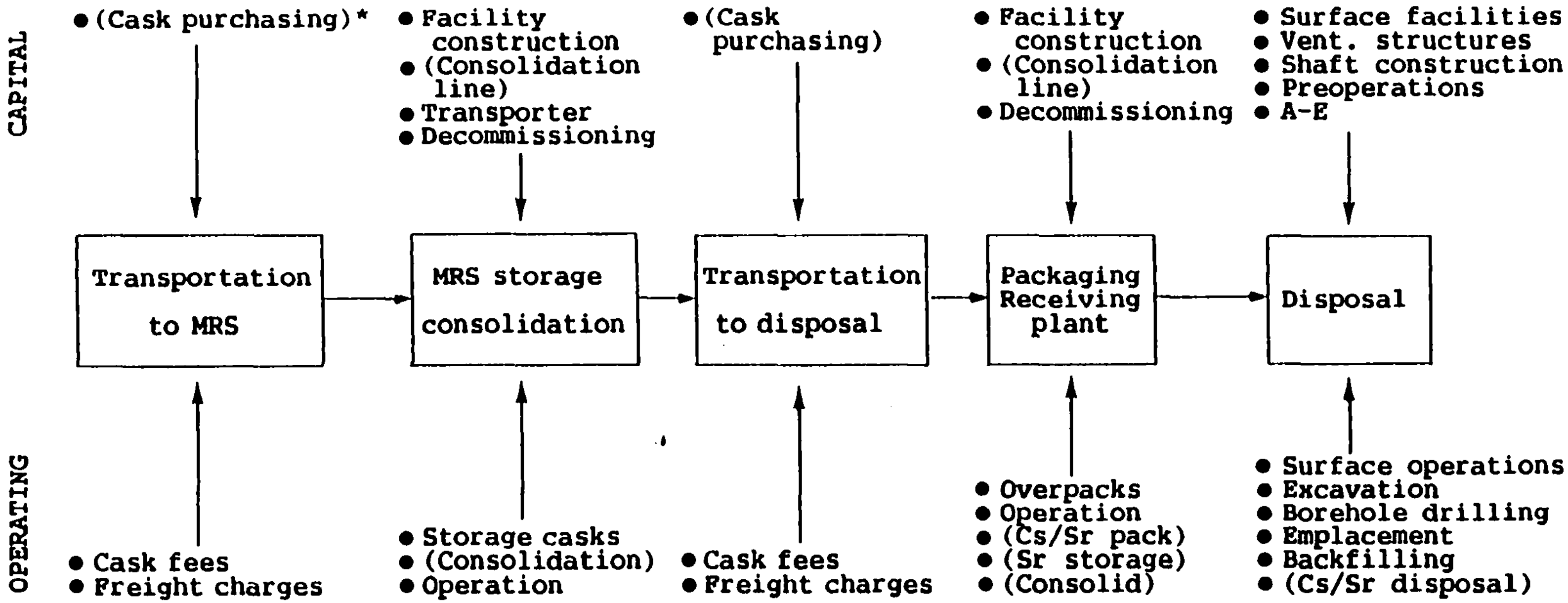
The transportation costs, which are similarly calculated for the two possible transportation operations that can take place, are made up of two different components, namely the cost of cask leasing and the cost of train freight.

In existing studies of cost of SF transportation it is assumed that the transportation casks will be leased from the manufacturing company. The rental cost estimates include the amortization of the cask, for a cask usage of 292 days per year, maintenance and inspection after each SF shipment, and licensing costs. The baseline estimated cost is of $4990 per day. The cask leasing cost per shipment will depend on the number of days spent in that particular shipment. The DOE estimated the number of days per shipment depending upon the




*Items in parentheses are optional.

FIGURE 27. Components of total cost in each operation for a storage facility co-located with the repository

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*Items in parentheses are optional.

FIGURE 28. Components of total cost in each operation for a storage facility not co-located with the repository

distance and the average rail mileage expected for such a special type of transportation. Using DOE data (33) the average mileage per day for a round trip (one way with the cask loaded with SF and one way with empty casks) is 75 miles. The number of days per shipment is then calculated by dividing the one-way distance by 75 plus two additional days for loading/unloading operations. Freight charges depend also on the total distance covered. The freight cost, however, will be different for a loaded or an empty cask, since special security requirements are needed for transportation of spent nuclear fuel. The freight charges are calculated as a function of the distance and the weight transported. The weight of an empty reference cask is 79,400 Kgs, of a cask loaded with 3.227 MTHM (unconsolidated fuel)is 84,200 Kgs, and for a cask loaded with 9.68 MTHM of consolidated spent fuel, 90,700 Kgs. The shipping cost per 1000 Kg when the cask is loaded is calculated:

$$\text{1987 dollars/1000 Kg} = 4.10\ (d^{0.5860})$$

and for an empty cask:

$$\text{1987 dollars/1000 Kg} = 3.75\ (d^{0.5895})$$

where d is the one-way distance.

The distances between the different locations have been estimated from data supplied in reference (123). In this source, average estimated distances from the power plants to Barnwell, S.C. are given, as well as total mileage and number of shipments from Barnwell to the possible repository locations of Deaf Smith Co., Hanford, and Yucca Mountain. To correct these distances to and from Barnwell to distances to and from Tennessee, the following assumptions have been made: the average mileage per shipment from power plants to an MRS in Tennessee is the same as the mileage to Barnwell, and the distance from the MRS in Tennessee to the 3 repository locations is about 500 miles shorter than those distances from Barnwell. The average mileages from power plants to the repository locations have not been corrected. The resulting distances, in miles (one-way), under these assumptions are:

| | |
|---|---|
| from power plants to the salt repository location | 1,500 miles |
| from power plants to the basalt repository location | 2,400 miles |
| from power plants to the tuff repository location | 2,250 miles |
| from power plants to MRS in Clinch River | 1,100 miles |
| from MRS to the salt repository location | 1,100 miles |
| from MRS to the basalt repository location | 2,500 miles |
| from MRS to the tuff repository location | 2,300 miles |

For a repository in granite, for which a particular location has not yet been identified, it is assumed that the distances are the same as those for the repository in salt, which is the closest to most of the power plants. Other assumptions made in calculating the transportation costs make reference to the schedules; transportation from the reactor sites to the MRS facility (regardless of its location) starts in 1998, and when applicable, transportation from the MRS to the repository is performed one year before disposal. The costs are then discounted accordingly.

## B. Storage Costs

The capital cost of the storage facility is estimated depending on its location and the possible existence of a consolidation line before storage. When the MRS is located far from the repository, the capital cost includes the construction of the waste receiving module and the waste handling and treatment module. The baseline cost estimate is $150 M with an additional $34 M if the consolidation of the spent fuel assemblies takes place at the MRS. If the MRS is co-located with the repository the waste treatment and handling building of the disposal site can service the storage facility as well. In this case the capital cost of this building is included in the MRS construction cost, for it would be built at the same time. The estimated baseline cost in this case is $180 M, to be increased by $34 M if the consolidation is performed before storage (if the consolidation is performed after storage, right before disposal, its cost is included as part of the packaging facility).

Construction costs of the MRS are divided into a period of 3 years and properly discounted (inflated, in this case, since construction takes place before the reference year of 1998). There is an additional item that is part of the capital equipment cost, the transporter/crane, valued at $2.7 M, for which the cost is incurred in 1997, one year before operations start. A decommissioning cost, calculated as a percentage of the capital cost is incurred at the end of the operational period.

Operating costs include the costs of the dry storage casks transported to the MRS location, the cost of operating the facility and support tasks and consolidation operations when applicable. If the MRS is located in the West, the cost of the cask on location is $893,600 and $863,000 if the MRS is in the East. Each year the cost of new casks needed for storage is evaluated by dividing the net increase in SF stored (if any) by 11 or 33 MTHM per cask for unconsolidated or consolidated spent fuel respectively. For each new cask, an additional cost of $2,790 is considered for the supporting concrete pad.

The costs of operating the facility are estimated at $9.05 M if the facility is not co-located with the repository, or 80 % of this amount if the MRS is co-located. The reduction accounts for the elimination of support services, such as administration and security, which are already included in the repository operating cost. The cost of consolidating the spent fuel assemblies is assumed independent of the MRS location, and the baseline value is estimated at $9,100/MTHM.

For the fractionation cycle, storage of Cs/Sr is required for a period of time. It is assumed that the empty casks from the SF storage can be used for this purpose as they are made available towards the end of the SF storage period. Thus new cask costs are only incurred if not enough casks from the SF storage are available. The rate of casks needed for storage of the solidified Cs/Sr is one cask per equivalent 70 MTHM. The cost of running the storage facility for Cs/Sr is estimated at 1/3 of the regular operating cost, for the number of canisters is smaller, as well as their size, the radioactivity levels are lower (less surveillance expenses), and finally there is no need for receiving/shipping installations, since the Cs/Sr waste form is generated, stored and disposed at the disposal site.

### C. Packaging Facility Costs

The packaging facility is always assumed to be located at the repository site. Because the overpacks are bulky and heavy, it would complicate operations to install them before storage or transportation. The capital cost of the packaging facility is linked to the costs of the storage facility. When the MRS is co-located, the waste receiving and handling facility that would otherwise be a part of the packaging facility exists as a component of the MRS. In this case the packaging line is also included in the same MRS building and the capital cost is already a part of the MRS cost.

When the storage facility is not co-located with the repository, a waste receiving/handling facility is included in the cost of the packaging facility. The reference capital cost depends upon the number of canisters to be processed per day, assuming 250 days/year of operation. For throughputs of less than 3 canisters (3 SF canisters or 9 short canisters of other waste forms) the cost is estimated at $108 M, and for larger processing rates, the cost estimate is $180 M. In the once-through cycle, when consolidation has not been performed at the MRS facility, an additional line, with a value of $34 M is included in the capital cost of the packaging facility. Construction of this facility is divided into 5 years and properly discounted. The five-year construction period is the same as for the rest of the repository surface installations.

Operation of the facility accounts for overpacking operations and receiving/handling operations, when required. The operating costs are divided into two different components; the first part, a fixed annual cost, and a second part which is proportional to the number of canisters processed per year. The costs of the two components for different throughputs are given in Appendix C.

The reference operating costs were based on estimates for a facility handling SF canisters and including the costs of the receiving and inspecting operations. However, when HLW/FHLW is handled instead of SF, some reduction in the operating costs can be expected. First of all, the HLW/FHLW canisters are smaller and lighter, thus requiring smaller equipment. Second, in a reprocessing cycle, since the reprocessing facility is also located at the disposal site, no receiving/treatment operations are to be performed in the packaging module. Finally, the inspection of the canisters before overpacking will likely be performed at the end of the solidification line in the reprocessing plant, so that this operation does not need be included as an operating expense of the packaging plant. The same comments about the receiving module and the canister inspection are applicable to the case of a once-through cycle with the MRS co-located with the repository. In all those situations, therefore, the fixed operating costs of the packaging facility are assumed to be 50 % of the reference costs, and for Cs/Sr waste form the same reduction is assumed for the package-dependent operating cost.

Another component of the annual cost of the facility is the cost of the overpacks, which is independent on MRS location but depends on the canister size and the waste form to be disposed. The unit canister costs for the different canister sizes considered is given in detail in Appendix C.

When consolidation is performed in the packaging facility, the reference cost is, as in the MRS case, \$9,100/MTHM consolidated. In the cost analysis model the costs of construction, consolidation, operations, and casks, are counted separately, and they are all later included as part of the repository final cost.

D. Disposal Costs

The first component of the disposal cost is the capital cost of the surface facilities, spread over a period of five years and properly discounted. All repository surface facilities except packaging (reprocessing plant and MRS when co-located are always excluded) are included in the initial capital cost. The baseline cost estimate is \$350 M, including ventilation structures.

The next capital expense item is the construction of the shafts, 5 for HLW/FHLW disposal and 4 for SF disposal. Costs per unit depth of the shafts, broken into sinking, lining, and hoisting are given, for the different rock formations, in Appendix C. Construction of the shafts extends over a period of 3 years, starting at the same time as the surface facilities and finishing two years before disposal operations begin.

The final item that is part of the construction costs is the preoperations, which includes the excavation of the central shaft hall area, the capital equipment cost of the mining and drilling machinery, and the excavation of the corridors for the first panel of disposal rooms. The baseline cost for the preoperations depends upon the host rock, and it is incurred two years before disposal operations begin. The total capital cost is increased by a percentage corresponding to the Architect-Engineering costs. At the end of the repository operations a decommissioning cost, estimated as a percentage of the total capital cost, is also calculated.

Operating costs are divided into operations of the surface facilities and underground operations. The baseline cost of operating the surface facilities is estimated at $21.21 M per year at full operation, and 50 % of this amount when only Cs/Sr is being disposed, in the fractionation cycle. The basis for the 50 % reduction is the assumption that in the fractionation cycle the same repository would be receiving waste that would otherwise go to the second disposal site. Therefore, only half of the operating expenses account for the operations related to Cs/Sr disposal.

The underground operating costs are further divided into five different operations, namely room and corridor excavation, borehole drilling, waste emplacement, mine ventilation, and room and corridor backfilling. Excavation and drilling costs are applied one year ahead of disposal and emplacement operations.

In calculating the excavation costs, the volume excavation requirements must be evaluated for each year. The required excavated volumes are different for different ages of the waste at disposal. The thermal loading is determined for each year and the pitch between boreholes is calculated to satisfy the thermal loading. Using the room dimensioning, the excavation requirements are estimated once the pitch has been calculated. The number of rooms required is also calculated, and with this information the corridor excavation volumes are estimated by multiplying the number of rooms by the room-to-room distance and the cross sectional area of the corridors. When the total excavated volume per year is known, the excavation costs are found by multiplying it by the excavation cost per unit volume, dependent upon the host rock.

Drilling costs depend upon the rock, the borehole diameter and the number of boreholes required per year. The depth of the boreholes is assumed to be 6 m for SF disposal and 5 m for other waste forms. Emplacement costs are estimated by multiplying the number of boreholes required per year times a unit cost per borehole, which depends on the type of waste. Details of the unit costs are given in Appendix C.

For reprocessing cycles, an additional excavation and emplacement cost need to be calculated, namely the disposal of TRU waste. The excavation volume is calculated by assuming the drums to be piled up in a disposal room, so that no drilling costs are applicable in this case.

Ventilation of the underground facility is required to maintain an acceptable working environment. The ventilation requirements are likely to depend upon the excavated volume and the thermal power emplaced in the repository. It is rather difficult to estimate the ventilation requirements for a generic parametric study, where the excavated volumes and thermal powers vary from case to case. In addition, it is not clear what requirements will be imposed on the disposal room temperatures once the waste has been emplaced in them. If these rooms were somehow isolated from the rest of the mine even before backfilling, ventilation might not be necessary. In trying to calculate the ventilation requirements a further complication appears due to the fact that the drift wall temperature and heat flux is delayed with respect to emplacement operations, and is time dependent.

Because the volume excavated is also proportional to the thermal power emplaced, the ventilation cost is estimated in this study in the form of a unit cost per year per unit thermal power at disposal. Only the thermal power emplaced in open rooms (not backfilled) is taken into account in estimating the total ventilation cost per year. The unit ventilation cost during the period in which both mining and emplacement operations take place is \$614/Kw disposed, and for the period when no mining is performed (backfilling period) the unit cost is \$409/Kw. Details on how these values were obtained are given in Appendix C. The ventilation costs are included, in the cost analysis output, as part of the underground operations.

A further ventilation, or even refrigeration, expense might be incurred in the event of waste retrieval. The retrieval operations, naturally, are not included in the repository cost analysis. Some studies have shown that it is possible in a reasonably short period of time to achieve the desired temperatures in the disposal room should retrieval operations be performed (124).

After a certain retrievability period, the rooms and corridors are to be backfilled. The backfilling costs, which are discounted according to the period of delay of backfilling, are estimated as a percentage of the excavation costs. The baseline percentage is assumed to be 25 %.

### E. Summary and Cost Analysis Procedure

A computer code has been developed to calculate all the cost components involved in the back end of the nuclear fuel cycle and calculate the total system costs. All costs are estimated in 1987 dollars and are discounted with respect to the year 1998, when an analysis with a discount rate different than 0 is desired. A printout of the expenses incurred by year of operation is optional. The case to be studied is selected in the input of the program.

Unless otherwise indicated in the input, the disposal operations are started in the year 2003. For a few cases, when the heat loading in the canister would exceed the maximum permissible at the time of disposal, the model automatically increases by one year at a time the delay of disposal, until the maximum loading requirement is met.

An optional feature of the program is the start of an optimization process, based on the delay of disposal. This optimization process has been made optional, because the user may be interested in analyzing the costs under the schedule proposed by the Department of Energy, excluding the possibility of further delays for economic reasons. When the optimization is triggered the program checks whether the total system costs can be decreased by increasing the delay of disposal by one year at a time. In the affirmative case, the process would continue until a minimum cost is found or until the disposal has been delayed for 30 years with respect to the original schedule, whichever comes first. The flow diagram used in the optimization process is shown in Figure 29.

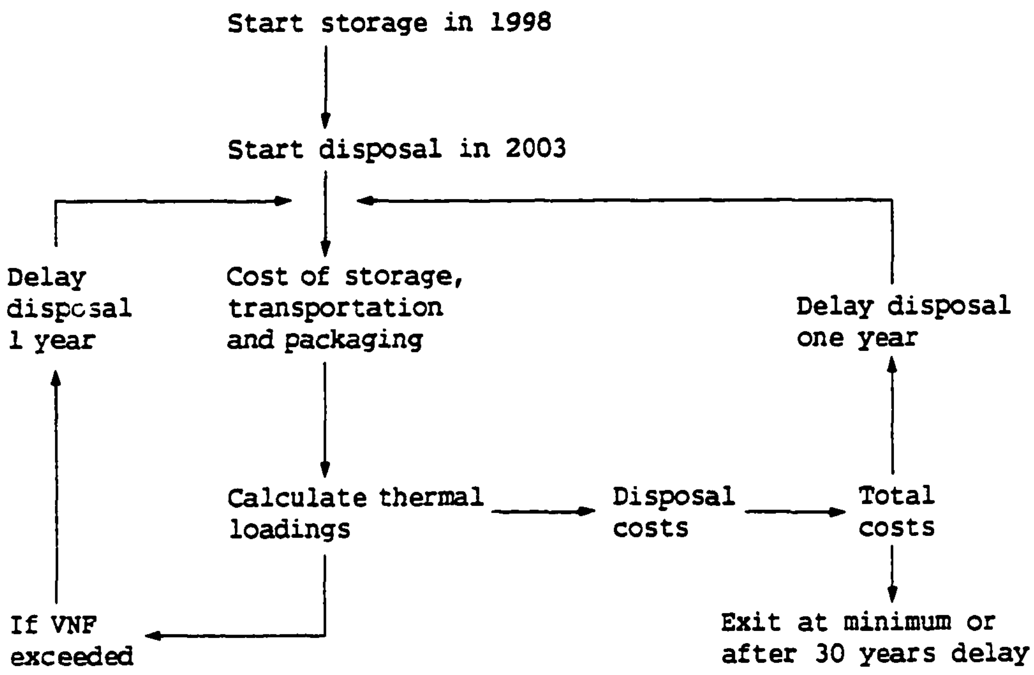


FIGURE 29. Block diagram of the economic optimization model

The basis for the optimization is the fact that by delaying disposal the excavation requirements decrease, at the same time that the disposal costs are deferred (discounted) one more year. This produces a certain amount of savings in disposal. On the other hand, however, the storage requirements increase by delaying the disposal operations, resulting in a cost increase. The possibility exists for the disposal savings to be larger than the increase in storage costs, and for the existence of a minimum total cost at a certain period of disposal delay. The 30-year limit for the optimization model is imposed as a political constraint. It is likely that delays of disposal longer than 30 years would not be politically acceptable. Indeed, the 30 year limit might already be too long, for there has already been opposition to the recent delay proposed by the DOE from 1998 to 2003 to start disposal operations. In particular, in the State of Tennessee, the fear exists that the MRS facility will become a permanent storage site for radioactive waste, and those fears will not disappear until actual construction of a repository starts.

The economic model is applied to the different cycles and scenarios (canister sizes, MRS location) considered within each cycle. To cover the uncertainties of the cost estimates and some design features, several variables can be changed from the input of the model. A summary of the parameters that can be changed, their baseline values when applicable and the ranges they are permitted to vary, is shown in Table 13. The results of the economic analysis are given and analyzed in Chapter VI, where special attention has been given to the comparison of the different cycles, rock types and facility locations.

TABLE 13. Variables to be selected in the input of the cost analysis model

| Variable | Baseline Value | Range |
|---|---|---|
| Rock type | | 4 possible rocks |
| Waste type | | 3 possible cycles |
| Canister size | | 3 for spent fuel |
| | | 9 for HLW/FHLW |
| Location of MRS | | 2 possible sites |
| Air gap(retrieval) | | Gap/No gap |
| Consolidation | | At MRS or packaging |
| Delay backfilling | 5 years | up to 25 years |
| Thermal factor | 1.5 | 1.3 to 1.7 |
| Repository fac. capital cost | $350 M | $305 M to $440 M |
| Surface facilities operating cost | $21.21 M | ± 20 % |
| Preoperations cost | Depends on rock | ± 20 % |
| Cask Leasing cost | $4,990 | Purchasing |
| Overpack cost | | With no Ti-code |
| Other capital cost | Depends on location | -13 % to + 26 % |
| Other oper. costs | Depends on location | ± 20 % |
| A-E cost | 10 % of capital | up to 20 % of capital |
| Decommissioning | 10 % of capital | up to 25 % of capital |
| Backfilling cost | 25 % of excavation | 20 % of excavation |
| Repository Depth | Depends on rock | Depends on rock |
| Room dimensions | 3 x 3 x 50 m | up to 4 x 5 x 100 m |

# VI. ECONOMIC ANALYSIS RESULTS AND DISCUSSION

The results of the application of the economic model to the different cycles and variations are presented in this chapter. The first section lists the numerical results for the three back end cycles in each of the 5 rocks, i.e., salt, granite, basalt, shallow tuff, and deep tuff. For each rock the ranges of costs are given, along with the sensitivity of the model to different parameters. Transportation costs have not been included in the listed results, in order to provide a better basis for comparison among rocks and cycles. The MRS is assumed to be co-located with the repository, and regardless of the fuel cycle chosen, consolidation takes place upon arrival of the spent fuel to the storage facility.

The costs of transportation and the effect of MRS location are analyzed in Section B of this chapter, along with discussion of particularly important parameters. The last part of Section B is a comparative summary of results for the different repository media and the different back end cycles.

## A. Results

There are a total of 21 possible canister types in each rock analysis, 3 for SF, 9 for HLW (3 sizes and 3 waste concentrations), and 9 for FHLW. In order to reduce the number of cases for the sensitivity analysis to a manageable size, one canister type has been selected for each cycle. The selection has been made under the criteria of minimum cost and satisfaction of thermal loading restrictions. For the reference canister types, the range of costs of storage and disposal for each possible cycle and rock have been calculated. Next, the sensitivities of the model to variations of different parameters, most notably the unit costs, have been obtained.

In the reference case, the baseline costs as given in Chapter V and Appendix C have been used to estimate the total storage plus disposal costs. To perform the sensitivity analyses, a range of variation of the unit costs had to be determined. The capital costs of the repository surface facilities were already estimated as a reference value with an uncertainty band -13 % to 26 %, and the same estimate has been used in the analysis. There were no estimates for the uncertainty band of other capital costs, and therefore the same percentage range of the repository facilities cost has been applied to them. An uncertainty of ± 20 % has been assumed for the operating costs, a reasonable range given that these costs were calculated from estimated manpower requirements. The costs that are calculated as a percentage of the capital expenditures, namely Architect-Engineering, decommissioning and backfilling, are given a range corresponding to the values most often used in the literature sources. The ranges for the three costs are 10 to 20 % for A-E, 15 to 25 % for decommissioning, and 20 to 25 % for backfilling costs. The baseline costs as well as the maximum and minimum ranges are listed in Table 14, along with the ranges of other parameters varied in the analysis. The upper and lower bounds of the storage plus disposal costs have been calculated using the maximum and minimum values listed in the table. In the sensitivity analyses, the maximum (minimum) value of the parameter analyzed has been used, whereas the rest of the variables were maintained at the reference setting.

It must be noted that there are two notable parameters absent from Table 14, namely the borehole drilling costs and the overpack costs. As mentioned in Chapter V, these are two items that deserve special consideration, and it might be inaccurate to assume they are bound by the same limits that are applied to operating and capital costs respectively. These two parameters are treated separately in Section B of this chapter and their reference cost values have been used in the sensitivity analysis. The discount rate, which is listed as one of the parameters, also deserves some further comment. It is common to perform cost analyses, for government operations in particular, with undiscounted costs. However, in the present study, the use of a 0 % discount rate would neglect the important aspect of operating schedules and the possible advantage of deferring some of the charges. A non-zero discount rate is thus used as the reference, and the value chosen is 2 %, a historical average for such type of industry (66), and slightly below the utility industry average of 2.75 % (125). An upper bound of 4 % is used, which would correspond to the unusually high rates of the mid-70s. The discount rates apply, of course, to constant dollar value accounting.

The economic model developed permits the selection of an optimization option, in which disposal is delayed beyond the year 2003 if the delay results in a reduction of the total storage plus disposal

TABLE 14. Parameter ranges for cost estimates and sensitivity analysis

| Parameter | Reference Value | Upper bound | Lower bound |
|---|---|---|---|
| Repository surface fac. capital cost | \$ 305 M[a] | +26 % | -13 % |
| Preoperations | Various | +26 % | -13% |
| MRS capital cost | \$ 215 M | +26 % | -13 % |
| Shaft contruc. cost | Various | +26 % | -13 % |
| Surface facilities operating cost | \$ 21.21 M | +20 % | -20% |
| MRS/Packaging Operating cost | Various | +20 % | -20 % |
| Other operating costs | Various | +20 % | -20 % |
| Delay backfilling | 5 years | 25 years | - |
| A-E cost | 10 % capital | 20 % capital | - |
| Decommissioning | 15 % capital | 25 % capital | - |
| Backfilling cost | 25 % capital | - | 20 % capital |
| Room-to-room distance | 12/15 m | 18/22 m | - |
| Room length | 50 m | 100 m | - |
| Thermal loading factor | 1.5 | 1.67 | 1.33 |
| Repository depth | Various | +10 % | -10 % |
| Room width | 3 m | 4 m | - |
| Discount rate | 2 % | 4 % | 0 % |

[a]Costs are given in 1987 dollars.

costs. However, political constraints may require that disposal operations start in 2003, regardless of the possibility of cost reduction by deferral. Two sets of results are therefore presented, one in which the delay of disposal is permitted to vary between 5 and 30 years, and another in which it is restricted to the 5-year reference schedule.

1. Results for a repository in salt

The reference cases have been analyzed for all possible canister types. In rock salt, the VNF-NF thermal loading constraints are not very restrictive, and as a result, only the HLW canister of 50 cm diameter and 20 % waste concentration must have a storage period longer than the default value of 5 years.[3] A minimum 8 years of storage would be required for this waste form, and all other types can be disposed after 5 years. Because the FF is the limiting field in salt, the excavation requirements do not change with canister type. The drilling and overpacking costs, however, increase with number of canisters to be disposed, resulting in lower costs the higher the waste content per canister.

For SF disposal, the canister type resulting in the lowest cost would be the largest, containing 12 assemblies. However, because the FF thermal loading is quite restrictive in salt, disposal of these large canisters results in very long pitches, over 50 m, which is in fact longer than the reference disposal room length. For this reason the canister containing 6 assemblies has been chosen as the reference

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[3] Storage starts in 1998, and disposal can start in 2003 at the earliest, so that the shortest (and reference) storage period is 5 years.

type for SF disposal. For HLW the lowest cost corresponds to the HLW-5020[4] canister, if 8 years of storage were acceptable. If delay of disposal beyond the year 2003 were not acceptable, the next best canister type is the HLW-4020, and this is used as the reference case. In the FHLW cycle, where the heat loading per canister has been considerably reduced by Cs/Sr removal, the largest possible canister is always the best choice, FHLW-5020. Indeed, the minimum pitch is almost always acceptable for disposal of the fractionated waste form.

The costs of the storage and disposal operations for the three cycles are given in Table 15 for the reference case and the upper and lower bounds. Both the optimization option and the fixed disposal schedule option are shown in the table. Note that in most of the cases the lowest cost corresponds to the minimum storage period of 5 years. Also, for HLW-5020 the least cost occurs at 8 years of disposal delay which is the minimum permissible for this canister design. When the least-cost situation does not correspond to the reference storage of 5 years, a minimum cost does not exist within the 30 year period used as an upper limit for the disposal delay.

The results of the sensitivity analyses are shown for the three different cycles in Tables 16, 17, and 18. The percentage variation with respect to the reference cost produced by changing a parameter is also given in the tables. Again, the two situations, fixed and variable schedules for disposal, are presented. Only the sensitivity

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[4] 50 cm-diameter canister with 20 % waste concentration.

TABLE 15. Storage plus disposal costs for a repository in salt

| Cycle | Canister type | Reference Cost[a] | DD[b] | Maximum Cost | DD | Minimum Cost | DD |
|---|---|---|---|---|---|---|---|
| FIXED DISPOSAL SCHEDULE | | | | | | | |
| SF | 6 a/c | 4,179 | 5 | 5,133 | 5 | 3,206 | 5 |
| HLW | 4020 | 3,377 | 5 | 4,202 | 5 | 2,548 | 5 |
| FHLW | 5020 | 3,894 | 5 | 4,823 | 5 | 2,951 | 5 |
| VARIABLE DISPOSAL SCHEDULE | | | | | | | |
| SF | 6 a/c | 4,179 | 5 | 5,133 | 5 | 3,052 | 30 |
| HLW | 4020 | 3,377 | 5 | 4,202 | 5 | 2,548 | 5 |
| HLW | 5020 | 3,329 | 8 | 4,199 | 8 | 2,651 | 8 |
| FHLW | 5020 | 3,706 | 30 | 4,823 | 5 | 2,642 | 30 |

[a]Costs in millions of 1987 dollars discounted with respect to the year 1998; discount rate: 2 %.

[b]DD - delay of disposal, in years.

to the parameters that change the optimum delay of disposal from the reference value of 5 have an entry in the variable schedules option. The parameters not listed in this option result in the same cost estimates given in the fixed disposal schedule alternative. The parameters whose variation result in total cost variations of less than 1 % with respect to the reference value, are all listed as a single entry.

In all three cycles, the model shows the highest sensitivity to the discount rate, which can result in cost variations in 1987 dollars of 30 % or more. Naturally, a low discount rate results in a higher cost. The delay of disposal room backfilling, from 5 to 25 years after emplacement can result in high cost penalties, except in the FHLW cycle, where the excavation requirements are at a minimum and half the operations (disposal of Cs/Sr) are performed with a 30-year delay. Unit costs, both operating and capital, result in moderate variations in the total cost, usually less than 1/4 of the unit cost change. The sensitivity is higher the larger the reference value of the parameter and the sooner the cost is incurred. In general, excavation and thermal loading parameters have a very moderate effect on the final storage plus disposal cost. Their effect is seen to be more important for SF disposal, the waste form requiring larger excavation volumes.

Aside from the discount rate and the delay of backfilling, there is an additional parameter that has a strong effect on the results of the economic model, i.e., the capital cost of the MRS facility. Its importance stems from the fact that a decrease in this cost may result in the possibility of reducing the total cost by delaying disposal, if that is permitted. When this occurs, the percentage variation of the total cost with respect to the reference value is already a two-digit figure. Although the capital cost of the MRS facility is of the same order of magnitude as the repository facilities, the cost of the storage casks, rather high, is part of the capital equipment cost of the storage facility, and was also changed in the sensitivity analysis.

TABLE 16. Sensitivity analysis in salt, SF disposal, 6 a/c

| Parameter | Reference Cost[a] | DD[b] | PARAMETER High Cost | High Change % | High DD | SETTING Low Cost | Low Change % | Low DD |
|---|---|---|---|---|---|---|---|---|
| FIXED DISPOSAL SCHEDULE | | | | | | | | |
| Discount rate | 4,179 | 5 | 3,296 | -27.0 | 5 | 5,576 | +33.0 | 5 |
| Backfill delay | | | 4,805 | +15.0 | 5 | | | |
| Surf. cap. cost | | | 4,303 | +3.0 | 5 | 4,116 | -1.5 | 5 |
| MRS capital cost | | | 4,370 | +4.6 | 5 | 4,013 | -4.0 | 5 |
| Surf. oper. cost | | | 4,276 | +2.3 | 5 | 4,081 | -2.3 | 5 |
| MRS oper. cost | | | 4,370 | +4.6 | 5 | 3,986 | -4.6 | 5 |
| Underground oper. | | | 4,302 | +2.9 | 5 | 4,056 | -2.9 | 5 |
| Shaft contruc. | | | 4,230 | +1.2 | 5 | 4,127 | -1.2 | 5 |
| A-E cost | | | 4,249 | +1.7 | 5 | | | |
| Thermal factor | | | 4,220 | +1.0 | 5 | 4,112 | -1.6 | 5 |
| Room length | | | 4,072 | -2.6 | 5 | | | |
| Depth | | | 4,133 | -1.1 | 5 | 4,226 | +1.1 | 5 |
| Room width | | | 4,276 | +2.3 | 5 | | | |
| Room-room dist. | | | 4,085 | -2.2 | 5 | | | |
| Others | | | | ≤ 1.0 | 5 | | ≤ 1.0 | 5 |
| VARIABLE DISPOSAL SCHEDULE | | | | | | | | |
| Discount rate | 4,179 | 5 | 2,724 | -35.0 | 30 | 5,576 | +33.0 | 5 |
| Backfill delay | | | 4,521 | +8.2 | 30 | | | |
| MRS capital cost | | | 4,370 | +4.6 | 5 | 3,630 | -13.1 | 30 |

[a]Costs in millions of 1987 dollars discounted from 1998; discount rate: 2 %.

[b]DD- delay disposal, in years.

When both the building and the storage cask costs decrease, the storage cost increase by one more year of storage is lower than in the reference case. Because of that, the savings attained in the disposal operations by delaying them one more year are higher than the storage

TABLE 17. Sensitivity analysis in salt, HLW-4020

| Parameter | Reference Cost[a] | DD | High Cost | High Change % | High DD | Low Cost | Low Change % | Low DD |
|---|---|---|---|---|---|---|---|---|
| FIXED DISPOSAL SCHEDULE | | | | | | | | |
| Discount rate | 3,377 | 5 | 2,748 | -19.0 | 5 | 4,370 | +29.7 | 5 |
| Backfill delay | | | 3,801 | +12.6 | 5 | | | |
| Surf. cap. cost | | | 3,501 | +3.7 | 5 | 3,314 | -1.9 | 5 |
| MRS capital cost | | | 3,568 | +5.7 | 5 | 3,211 | -4.9 | 5 |
| Surf. oper. cost | | | 3,475 | +2.9 | 5 | 3,279 | -2.9 | 5 |
| MRS oper. cost | | | 3,547 | +5.0 | 5 | 3,207 | -5.0 | 5 |
| Other oper. costs | | | 3,423 | +1.4 | 5 | 3,330 | -1.4 | 5 |
| Shaft contruc. | | | 3,436 | +1.8 | 5 | 3,318 | -1.8 | 5 |
| A-E cost | | | 3,450 | +2.2 | 5 | | | |
| Other | | | | ≤ 1.0 | 5 | | ≤ 1.0 | 5 |
| VARIABLE DISPOSAL SCHEDULE | | | | | | | | |
| Discount rate | 3,377 | 5 | 2,507 | -26.0 | 30 | 4,370 | +29.4 | 5 |
| MRS capital cost | | | 3,568 | +5.7 | 5 | 3,115 | -6.6 | 30 |

[a]Costs in millions of 1987 dollars discounted from 1998; discount rate: 2%.

cost increase. It must be said at this point that in all the cases analyzed the increase in storage costs by deferring disposal one year is a number relatively close to the disposal savings. This can be observed by noting that, for example, for HLW disposal and a low storage capital cost, the difference in total cost by disposing at 5 or at 30 years amounts only to $94 M, or less than 3 % of the total cost. Drastic cost reductions are not obtained by deferring the disposal operations.

TABLE 18. Sensitivity analysis in salt, FHLW-5020

| Parameter | Reference Cost[a] | DD | PARAMETER SETTING High Cost | Change % | DD | Low Cost | Change % | DD |
|---|---|---|---|---|---|---|---|---|
| FIXED DISPOSAL SCHEDULE | | | | | | | | |
| Discount rate | 3,894 | 5 | 3,046 | -24.8 | 5 | 5,460 | +40.2 | 5 |
| Backfill delay | | | 4,039 | +3.7 | 5 | | | |
| Surf. cap. cost | | | 4,015 | +3.1 | 5 | 3,833 | -1.6 | 5 |
| MRS capital cost | | | 4,196 | +7.8 | 5 | 3,618 | -7.1 | 5 |
| Surf. oper. cost | | | 4,009 | +2.9 | 5 | 3,799 | -2.9 | 5 |
| MRS oper. cost | | | 4,081 | +4.8 | 5 | 3,710 | -4.8 | 5 |
| Shaft contruc. | | | 3,953 | +1.5 | 5 | 3,835 | -1.5 | 5 |
| A-E cost | | | 3,953 | +1.5 | 5 | | | |
| Others | | | | ≤ 1.0 | 5 | | ≤ 1.0 | 5 |
| VARIABLE DISPOSAL SCHEDULE | | | | | | | | |
| Discount rate | 3,706 | 30 | 2,488 | -32.9 | 30 | 5,460 | +47.3 | 5 |
| Backfill delay | | | 3,768 | +1.7 | 30 | | | |
| Surf. cap. cost | | | 3,779 | +1.9 | 30 | 3,668 | -1.0 | 30 |
| MRS capital cost | | | 4,196 | +13.2 | 5 | 3,137 | -15.4 | 30 |
| Surf. oper. cost | | | 3,776 | +1.9 | 30 | 3,636 | -1.9 | 30 |
| MRS oper. cost | | | 3,887 | +4.9 | 30 | 3,526 | -4.9 | 30 |
| A-E cost | | | 3,750 | +1.2 | 30 | | | |
| Others | | | | ≤ 1.0 | 30 | | ≤ 1.0 | 30 |

[a]Costs in millions of 1987 dollars discounted from 1998; discount rate: 2 %.

## 2. Results for a repository in granite

The canister selection analysis indicates that only the HLW-5020 canister is thermally restricted. The minimum storage period for this canister type would be about 9 years, and could not be used in case of fixed disposal schedules. HLW-4020 is the next best choice and disposal can start in 2003. All SF and FHLW canisters are acceptable, although the pitch of SF canisters with 12 assemblies is again rather large, and it might be preferable to use the medium size canister, containing 6 assemblies. Using the largest canister for FHLW presents no problems. The cost ranges are given for the different cycles and canister types in Table 19. The sensitivity analyses, however, were performed for the SF canister with 6 a/c, HLW-4020 and FHLW-5020, which provides common ground for comparison with other rocks.

The results in granite are qualitatively similar to those for a repository in salt, with a lower cost range if a reprocessing cycle is selected and a preference for delaying the disposal as long as politically acceptable if the fractionation cycle is chosen. The results of the sensitivity analyses are shown in Tables 20, 21, and 22 for the once-through, reprocesssing, and fractionating cycles respectively.

The most important parameters are the discount rate and the MRS capital and operating costs. The sensitivity of the model becomes larger when a change in a parameter has the power to change the optimum storage period, since it gives the oportunity to discount a part of the costs. In general terms the FHLW cycle is the least sensitive to parameter changes, except for the discount rate and the storage facility costs. It must also be observed that none of the excavation parameters, namely room dimensions and thermal loading variations affect the results significantly; the changes in total storage plus disposal costs are always less than 1 % of the reference value.

TABLE 19. Storage plus disposal costs for a repository in granite

| Cycle | Canister type | Reference Cost[a] | DD[b] | Maximum Cost | DD | Minimum Cost | DD |
|---|---|---|---|---|---|---|---|
| FIXED DISPOSAL SCHEDULE | | | | | | | |
| SF | 6 a/c | 4,020 | 5 | 4,836 | 5 | 3,364 | 5 |
| SF | 12 a/c | 3,716 | 5 | 4,573 | 5 | 3,036 | 5 |
| HLW | 4020 | 3,490 | 5 | 4,286 | 5 | 2,870 | 5 |
| FHLW | 5020 | 3,962 | 5 | 4,873 | 5 | 3,219 | 5 |
| VARIABLE DISPOSAL SCHEDULE | | | | | | | |
| SF | 6 a/c | 4,020 | 5 | 4,836 | 5 | 3,149 | 30 |
| SF | 12 a/c | 3,716 | 5 | 4,573 | 5 | 2,934 | 30 |
| HLW | 4020 | 3,490 | 5 | 4,286 | 5 | 2,857 | 30 |
| HLW | 5020 | 3,475 | 9 | 4,372 | 9 | 2,767 | 12 |
| FHLW | 5020 | 3,744 | 30 | 4,873 | 5 | 2,805 | 30 |

[a]Costs in millions of 1987 dollars discounted from 1998; discount rate: 2 %.

[b]DD - delay of disposal, in years.

Significant cost increases are incurred if the room backfilling is delayed up to 25 years, in the cases of SF and HLW disposal in particular.

TABLE 20. Sensitivity analysis in granite, SF disposal, 6 a/c

| Parameter | Reference Cost[a] | DD[b] | PARAMETER SETTING High Cost | High Change % | High DD | Low Cost | Low Change % | Low DD |
|---|---|---|---|---|---|---|---|---|
| FIXED DISPOSAL SCHEDULE | | | | | | | | |
| Discount rate | 4,020 | 5 | 3,184 | -20.8 | 5 | 5,356 | +33.2 | 5 |
| Backfill delay | | | 4,560 | +13.4 | 5 | | | |
| Surf. cap. cost | | | 4,160 | +3.5 | 5 | 3,950 | -1.7 | 5 |
| MRS capital cost | | | 4,212 | +4.8 | 5 | 3,854 | -4.1 | 5 |
| Surf. oper. cost | | | 4,118 | +2.4 | 5 | 3,922 | -2.4 | 5 |
| MRS oper. cost | | | 4,212 | +4.8 | 5 | 3,828 | -4.8 | 5 |
| Underground oper. | | | 4,102 | +2.0 | 5 | 3,937 | -2.1 | 5 |
| A-E cost | | | 4,087 | +1.7 | 5 | | | |
| Room length | | | 3,963 | -1.4 | 5 | | | |
| Others | | | | ≤ 1.0 | 5 | | ≤ 1.0 | 5 |
| VARIABLE DISPOSAL SCHEDULE | | | | | | | | |
| Discount rate | 4,020 | 5 | 2,678 | -33.4 | 30 | 5,356 | +33.2 | 5 |
| Backfill delay | | | 4,373 | +8.8 | 30 | | | |
| MRS capital cost | | | 4,212 | +4.8 | 5 | 3,534 | -12.1 | 30 |

[a]Costs in millions of 1987 dollars discounted from 1998; discount rate: 2 %.

[b]DD- delay disposal, in years.

### 3. Results for a repository in basalt

Basalt is the rock that required the most serious thermal constraints. Because of that, several canister types cannot be disposed in this host rock with acceptable periods of storage. Among the SF types, the large canister (12 assemblies) would require more than 30 years of storage, resulting in an unacceptably long delay of

TABLE 21. Sensitivity analysis in granite, HLW-4020

| Parameter | Reference Cost[a] | DD | PARAMETER SETTING High Cost | Change % | DD | Low Cost | Change % | DD |
|---|---|---|---|---|---|---|---|---|
| FIXED DISPOSAL SCHEDULE | | | | | | | | |
| Discount rate | 3,490 | 5 | 2,817 | -19.3 | 5 | 4,565 | +30.8 | 5 |
| Backfill delay | | | 3,943 | +13.0 | 5 | | | |
| Surf. cap. cost | | | 3,631 | +4.0 | 5 | 3,421 | -2.0 | 5 |
| MRS capital cost | | | 3,682 | +5.5 | 5 | 3,325 | -4.7 | 5 |
| Surf. oper. cost | | | 3,588 | +2.8 | 5 | 3,392 | -2.8 | 5 |
| MRS oper. cost | | | 3,660 | +4.9 | 5 | 3,320 | -4.9 | 5 |
| Underground costs | | | 3,550 | +1.7 | 5 | 3,430 | -1.7 | 5 |
| A-E cost | | | 3,560 | +2.0 | 5 | | | |
| Other | | | | ≤ 1.0 | 5 | | ≤ 1.0 | 5 |
| VARIABLE DISPOSAL SCHEDULE | | | | | | | | |
| Discount rate | 3,490 | 5 | 2,533 | -27.7 | 30 | 4,565 | +30.8 | 5 |
| Backfill delay | | | 3,936 | +12.8 | 9 | | | |
| MRS capital cost | | | 3,682 | +5.5 | 5 | 3,167 | -9.3 | 30 |

[a]Costs in millions of 1987 dollars discounted from 1998; discount rate: 2%.

disposal. The canister containing 6 assemblies is acceptable from the thermal point of view and results in lower costs than the small, 3-assembly, canister. Among the HLW canisters, the HLW-5020 requires again delays in disposal of over 30 years. Canisters of the same size and lower concentration, such as the HLW-5015 and HLW-5010 still require long storage periods, 24 and 10 years respectively, whereas the HLW-4020 canister needs a minimum delay of disposal of about 18 years. Among the thermaly less restricted canisters the least-cost choice

TABLE 22. Sensitivity analysis in granite, FHLW-5020

| Parameter | Reference Cost[a] | DD | High Cost | High Change % | DD | Low Cost | Low Change % | DD |
|---|---|---|---|---|---|---|---|---|
| FIXED DISPOSAL SCHEDULE | | | | | | | | |
| Discount rate | 3,962 | 5 | 3,070 | -22.5 | 5 | 5,601 | +41.4 | 5 |
| Backfill delay | | | 4,112 | +3.8 | 5 | | | |
| Surf. cap. cost | | | 4,094 | +3.3 | 5 | 3,889 | -1.8 | 5 |
| MRS capital cost | | | 4,259 | +7.5 | 5 | 3,681 | -7.1 | 5 |
| Surf. oper. cost | | | 4,082 | +3.0 | 5 | 3,842 | -3.0 | 5 |
| MRS oper. cost | | | 4,144 | +4.6 | 5 | 3,772 | -4.6 | 5 |
| A-E cost | | | 4,026 | +1.6 | 5 | | | |
| Others | | | | ≤ 1.0 | 5 | | ≤ 1.0 | 5 |
| VARIABLE DISPOSAL SCHEDULE | | | | | | | | |
| Discount rate | 3,744 | 30 | 2,496 | -33.3 | 30 | 5,601 | +49.6 | 5 |
| Backfill delay | | | 3,813 | +1.8 | 30 | | | |
| Surf. cap. cost | | | 3,828 | +2.2 | 30 | 3,702 | -1.1 | 30 |
| MRS capital cost | | | 4,259 | +13.8 | 5 | 3,175 | -15.2 | 30 |
| Surf. oper. cost | | | 3,814 | +1.9 | 30 | 3,674 | -1.9 | 30 |
| MRS oper. cost | | | 3,925 | +4.8 | 30 | 3,564 | -4.8 | 30 |
| A-E cost | | | 3,786 | +1.2 | 30 | | | |
| Others | | | | ≤ 1.0 | 30 | | ≤ 1.0 | 30 |

[a]Costs in millions of 1987 dollars discounted from 1998; discount rate: 2 %.

would be the HLW-4015, a 20 cm-radius canister with 15 % of waste oxides concentration in the glass. To be precise, the HLW-4015 can only be disposed after almost 6 years of storage, so that disposal operations could only start in the second half of the year 2003, which is assumed here to be acceptable, and it is used as the reference type. The FHLW canisters are never restricted by the thermal loading constraints and the larger the canister (the lower the number of canisters per year) the lower the total cost. The FHLW-5020 is again the reference canister selected.

Because of the more severe thermal loading restrictions, the excavation requirements are larger in basalt than in granite, resulting in slightly higher disposal costs. The cost ranges for the three different cycles are given in Table 23. Note that in the table, the reference disposal delay for the waste form HLW-4015 appears as 6 years, the result of the slight thermal restriction discussed above.

Another important feature in basalt is the fact that when the disposal schedules are flexible, a minimum cost situation exists for the SF and HLW reference cases at storage periods longer than the minimum. This characteristic appears to be unique for basalt, the reason being the more restrictive thermal loadings. Indeed, because the thermal loadings are lower for basalt compared to any other repository medium, the savings in disposal costs when the waste is aged become more significant and offset the storage cost increases.

The results of the sensitivity analyses for the three cycles are given in Tables 24, 25, and 26. The total costs in basalt appear to be slightly more sensitive to variations of the different parameters than those in other repository media. In particular, variations of more than 1 % are observed for changes in several of the excavation parameters.

For SF and HLW disposal the sensitivity analysis shows a different trend from what is observed in the other rocks. It can be seen from

TABLE 23. Storage plus disposal costs for a repository in basalt

| Cycle | Canister type | Reference Cost[a] | Reference DD[b] | Maximum Cost | Maximum DD | Minimum Cost | Minimum DD |
|---|---|---|---|---|---|---|---|
| FIXED DISPOSAL SCHEDULE | | | | | | | |
| SF | 6 a/c | 4,435 | 5 | 5,288 | 5 | 3,720 | 5 |
| HLW | 4015 | 3,922 | 6 | 4,787 | 6 | 3,236 | 6 |
| FHLW | 5020 | 4,108 | 5 | 5,063 | 5 | 3,346 | 5 |
| VARIABLE DISPOSAL SCHEDULE | | | | | | | |
| SF | 6 a/c | 4,350 | 17 | 5,288 | 5 | 3,303 | 30 |
| HLW | 4015 | 3,913 | 9 | 4,787 | 6 | 2,990 | 30 |
| FHLW | 5020 | 3,832 | 30 | 5,063 | 5 | 2,879 | 30 |

[a]Costs in millions of 1987 dollars discounted from 1998; discount rate: 2 %.

[b]DD - delay of disposal, in years.

the tables that most cases result in an optimum delay of disposal if the disposal schedules are not fixed. Variation of parameters affects this optimum delay period by a few years, but only drastically in the cases of the three strong parameters, the discount rate, the MRS capital costs and the delay of room backfilling. The third cycle, FHLW, shows the same pattern as in other rocks, and the preferred disposal schedule is always the more delayed. Only the discount rate and the MRS capital costs can change that.

TABLE 24. Sensitivity analysis in basalt, SF disposal, 6 a/c

| Parameter | Reference Cost[a] | Reference DD[b] | PARAMETER SETTING High Cost | High Change % | High DD | Low Cost | Low Change % | Low DD |
|---|---|---|---|---|---|---|---|---|
| FIXED DISPOSAL SCHEDULE | | | | | | | | |
| Discount rate | 4,435 | 5 | 3,488 | -21.4 | 5 | 5,934 | +33.8 | 5 |
| Backfill delay | | | 5,076 | +14.5 | 5 | | | |
| Surf. cap. cost | | | 4,579 | +3.3 | 5 | 4,363 | -1.6 | 5 |
| MRS capital cost | | | 4,627 | +4.3 | 5 | 4,269 | -3.7 | 5 |
| Surf. oper. cost | | | 4,533 | +2.2 | 5 | 4,337 | -2.2 | 5 |
| MRS oper. cost | | | 4,627 | +4.3 | 5 | 4,243 | -4.3 | 5 |
| Underground oper. | | | 4,565 | +2.9 | 5 | 4,305 | -2.9 | 5 |
| Shaft contruc. | | | 4,479 | +1.0 | 5 | 4,390 | -1.0 | 5 |
| A-E cost | | | 4,513 | +1.8 | 5 | | | |
| Thermal factor | | | 4,479 | +1.0 | 5 | 4,364 | -1.6 | 5 |
| Room length | | | 4,314 | -2.7 | 5 | | | |
| Room-room dist. | | | 4,365 | -1.6 | 5 | | | |
| Others | | | | ≤ 1.0 | 5 | | ≤ 1.0 | 5 |
| VARIABLE DISPOSAL SCHEDULE | | | | | | | | |
| Discount rate | 4,350 | 17 | 2,767 | -36.4 | 30 | 5,934 | +36.4 | 5 |
| Backfill delay | | | 4,588 | +5.5 | 30 | | | |
| Surf. cap. cost | | | 4,459 | +2.5 | 21 | 4,293 | -1.3 | 16 |
| MRS capital cost | | | 4,627 | +6.4 | 5 | 3,714 | -14.6 | 30 |
| Surf. oper. cost | | | 4,428 | +1.8 | 20 | 4,272 | -1.8 | 15 |
| MRS oper. cost | | | 4,538 | +4.3 | 17 | 4,163 | -4.3 | 18 |
| Underground oper. | | | 4,431 | +1.9 | 20 | 4,262 | -2.0 | 14 |
| A-E cost | | | 4,410 | +1.4 | 20 | | | |
| Room lentght | | | 4,272 | -1.8 | 14 | | | |
| Room-to-room dist | | | 4,299 | -1.2 | 17 | | | |

[a]Costs in millions of 1987 dollars discounted from 1998; discount rate: 2 %.

[b]DD- delay disposal, in years.

TABLE 25. Sensitivity analysis in basalt, HLW-4015

| Parameter | Reference Cost[a] | DD | PARAMETER SETTING High Cost | High Change % | DD | Low Cost | Low Change % | DD |
|---|---|---|---|---|---|---|---|---|
| FIXED DISPOSAL SCHEDULE | | | | | | | | |
| Discount rate | 3,922 | 6 | 3,109 | -20.7 | 6 | 5,214 | +32.9 | 6 |
| Backfill delay | | | 4,406 | +12.3 | 6 | | | |
| Surf. cap. cost | | | 4,064 | +3.6 | 6 | 3,852 | -1.8 | 6 |
| MRS capital cost | | | 4,141 | +5.6 | 6 | 3,716 | -5.3 | 6 |
| Surf. oper. cost | | | 4,018 | +2.5 | 6 | 3,826 | -2.5 | 6 |
| MRS oper. cost | | | 4,098 | +4.5 | 6 | 3,746 | -4.5 | 6 |
| Underground oper. | | | 4,004 | +2.1 | 6 | 3,840 | -2.1 | 6 |
| Shaft contruc. | | | 3,973 | +1.3 | 6 | 3,871 | -1.3 | 6 |
| A-E cost | | | 4,002 | +2.0 | 6 | | | |
| Room length | | | 3,837 | -2.2 | 6 | | | |
| Other | | | | ≤ 1.0 | 6 | | ≤ 1.0 | 6 |
| VARIABLE DISPOSAL SCHEDULE | | | | | | | | |
| Discount rate | 3,913 | 9 | 2,623 | -33.0 | 30 | 5,214 | +33.3 | 6 |
| Backfill delay | | | 4,142 | +5.9 | 30 | | | |
| Surf. cap. cost | | | 4,043 | +3.3 | 11 | 3,846 | -1.7 | 8 |
| MRS capital cost | | | 4,141 | +5.8 | 6 | 3,370 | -13.9 | 30 |
| Surf. oper. cost | | | 4,004 | +2.3 | 10 | 3,822 | -2.3 | 8 |
| MRS oper. cost | | | 4,089 | +4.5 | 9 | 3,737 | -4.5 | 9 |
| Under. oper. cost | | | 3,978 | +1.7 | 12 | 3,840 | -1.9 | 9 |
| Shaft contruc. | | | 3,961 | +1.2 | 10 | | | |
| A-E cost | | | 3,987 | +1.9 | 10 | | | |

[a]Costs in millions of 1987 dollars discounted from 1998; discount rate: 2%.

## 4. Results for a repository in tuff

The total cost estimates for the two possible repositories in tuff are very similar. The main differences come from the slightly different permissible thermal loadings that would apply at different

TABLE 26. Sensitivity analysis in basalt, FHLW-5020

| Parameter | Reference Cost[a] | Reference DD | High Cost | High Change % | High DD | Low Cost | Low Change % | Low DD |
|---|---|---|---|---|---|---|---|---|
| FIXED DISPOSAL SCHEDULE | | | | | | | | |
| Discount rate | 4,108 | 5 | 3,208 | -21.9 | 5 | 5,769 | +40.4 | 5 |
| Backfill delay | | | 4,260 | +3.7 | 5 | | | |
| Surf. cap. cost | | | 4,250 | +3.5 | 5 | 4,038 | -1.7 | 5 |
| MRS capital cost | | | 4,410 | +7.4 | 5 | 3,832 | -6.7 | 5 |
| Surf. oper. cost | | | 4,223 | +2.8 | 5 | 3,993 | -2.8 | 5 |
| MRS oper. cost | | | 4,295 | +4.6 | 5 | 3,922 | -4.6 | 5 |
| Shaft contruc. | | | 4,160 | +1.3 | 5 | 4,056 | -1.3 | 5 |
| A-E cost | | | 4,190 | +2.0 | 5 | | | |
| Others | | | | ≤ 1.0 | 5 | | ≤ 1.0 | 5 |
| VARIABLE DISPOSAL SCHEDULE | | | | | | | | |
| Discount rate | 3,832 | 5 | 2,547 | -33.5 | 30 | 5,769 | +50.5 | 5 |
| Backfill delay | | | 3,902 | +1.8 | 30 | | | |
| Surf. cap. cost | | | 3,919 | +2.3 | 30 | 3,790 | -1.1 | 30 |
| MRS capital cost | | | 4,410 | +15.1 | 5 | 3,263 | -14.9 | 30 |
| Surf. oper. cost | | | 3,902 | +1.8 | 30 | 3,762 | -1.8 | 30 |
| MRS oper. cost | | | 4,013 | +4.7 | 30 | 3,653 | -4.7 | 30 |
| A-E cost | | | 3,878 | +1.7 | 30 | | | |
| Others | | | | ≤ 1.0 | 30 | | ≤ 1.0 | 30 |

[a]Costs in millions of 1987 dollars discounted from 1998; discount rate: 2 %.

depths, partially compensated by the different cost of shaft construction. The repository in deep tuff accepts higher thermal loadings, resulting in lower excavation requirements, but at the same time the shaft sinking costs are twice as high. Borehole drilling and emplacement operations depend on the number of canisters to be disposed, so that for equal canister types, the drilling and emplacement costs are the same. The results for both repositories in tuff are given in this section.

At both depths, the best choice for the SF canister appears to be the one containing 6 assemblies, although the 12-assembly canister, restricted by thermal loadings in shallow tuff, might be used, with a long pitch, in the repository at 700 m. The HLW-5020 canister cannot be used in any of the repositories without a long disposal delay, of about 15 years, and the reference type is again the HLW-4020 canister. As in all other rocks, the fractionated high-level waste canisters are not limited by the permissible thermal loadings, and the least-cost situation corresponds to the FHLW-5020 canister.

The baseline costs and their ranges are given in Table 27 for the repository at a depth of 350 m, and the costs for a 700-m deep repository are listed in Table 28. It can be seen that the reference costs, as well as the ranges, are very similar in both cases. The largest differences appear in the FHLW cycle, and in this case, the shallow repository would be favored; this is because the only difference in cost in the FHLW cycle is the shaft construction cost, higher for the deep repository. The excavation requirements, and costs, are the same in the case of the fractionation cycle, since the canister thermal loading is always very low and the minimum pitch can always be used.

The results of the sensitivity analyses are also very similar for the two repositories. As in other rocks, the most important parameters are the discount rate and the storage capital costs, which can also

TABLE 27. Storage plus disposal costs for a repository in shallow tuff

| Cycle | Canister type | Reference Cost[a] | DD[b] | Maximum Cost | DD | Minimum Cost | DD |
|---|---|---|---|---|---|---|---|
| FIXED DISPOSAL SCHEDULE | | | | | | | |
| SF | 6 a/c | 3,698 | 5 | 4,493 | 5 | 3,050 | 5 |
| HLW | 4020 | 3,318 | 5 | 4,089 | 5 | 2,701 | 5 |
| FHLW | 5020 | 3,741 | 5 | 4,632 | 5 | 3,018 | 5 |
| VARIABLE DISPOSAL SCHEDULE | | | | | | | |
| SF | 6 a/c | 3,698 | 5 | 4,493 | 5 | 2,908 | 30 |
| HLW | 4020 | 3,318 | 5 | 4,089 | 5 | 2,680 | 11 |
| FHLW | 5020 | 3,612 | 30 | 4,632 | 5 | 2,682 | 30 |

[a]Costs in millions of 1987 dollars discounted from 1998; discount rate: 2 %.

[b]DD - delay of disposal, in years.

produce changes in the optimum period of storage if the disposal delay is flexible. Since the estimated costs are so similar, the percentage variations produced by varying parameters are also very similar. Among the excavation dimensions and thermal loading parameters, only the room length results in a change of more than 1 % in the total cost. Because the results are so similar, only the sensitivity analysis tables for shallow tuff are given below, in Tables 29, 30, and 31, for SF, HLW and FHLW disposal respectively.

The sensitivity to variations of the shaft construction cost has

TABLE 28. Storage plus disposal costs for a repository in deep tuff

| Cycle | Canister type | Reference Cost[a] | Reference DD[b] | Maximum Cost | Maximum DD | Minimum Cost | Minimum DD |
|---|---|---|---|---|---|---|---|
| FIXED DISPOSAL SCHEDULE | | | | | | | |
| SF | 6 a/c | 3,670 | 5 | 4,487 | 5 | 3,020 | 5 |
| HLW | 4020 | 3,309 | 5 | 4,108 | 5 | 2,688 | 5 |
| FHLW | 5020 | 3,831 | 5 | 4,750 | 5 | 3,089 | 5 |
| VARIABLE DISPOSAL SCHEDULE | | | | | | | |
| SF | 6 a/c | 3,670 | 5 | 4,487 | 5 | 2,939 | 30 |
| HLW | 4020 | 3,309 | 5 | 4,108 | 5 | 2,687 | 6 |
| FHLW | 5020 | 3,667 | 30 | 4,750 | 5 | 2,726 | 30 |

[a]Costs in millions of 1987 dollars discounted from 1998; discount rate: 2 %.

[b]DD - delay of disposal, in years.

been given in the tables, even though the percentage change in the total cost is smaller than 1 %. However, the number in the tables are for shallow tuff. For deep tuff, where the shaft construction costs are doubled, the change in total cost due to 20 % changes in shaft contruction costs are twice the values indicated in the tables, or roughly, 1 %.

TABLE 29. Sensitivity analysis in tuff (350 m), SF disposal, 6 a/c

| Parameter | Reference Cost[a] | DD[b] | PARAMETER High Cost | Change % | DD | SETTING Low Cost | Change % | DD |
|---|---|---|---|---|---|---|---|---|
| FIXED DISPOSAL SCHEDULE | | | | | | | | |
| Discount rate | 3,698 | 5 | 2,928 | -20.8 | 5 | 4,916 | +32.9 | 5 |
| Backfill delay | | | 4,249 | +14.9 | 5 | | | |
| Surf. cap. cost | | | 3,835 | +3.7 | 5 | 3,630 | -1.8 | 5 |
| MRS capital cost | | | 3,890 | +5.2 | 5 | 3,533 | -4.5 | 5 |
| Surf. oper. cost | | | 3,796 | +2.7 | 5 | 3,600 | -2.7 | 5 |
| MRS oper. cost | | | 3,890 | +5.2 | 5 | 3,506 | -5.2 | 5 |
| Underground oper. | | | 3,786 | +2.4 | 5 | 3,611 | -2.4 | 5 |
| Shaft contruc. | | | 3,714 | +0.4 | 5 | 3,682 | -0.4 | 5 |
| A-E cost | | | 3,760 | +1.7 | 5 | | | |
| Room length | | | 3,626 | -2.0 | 5 | | | |
| Others | | | | ≤ 1.0 | 5 | | ≤ 1.0 | 5 |
| VARIABLE DISPOSAL SCHEDULE | | | | | | | | |
| Discount rate | 3,698 | 5 | 2,562 | -30.7 | 30 | 4,916 | +32.9 | 5 |
| Backfill delay | | | 4,194 | +13.4 | 24 | | | |
| MRS capital cost | | | 3,890 | +5.2 | 5 | 3,280 | -11.3 | 30 |

[a]Costs in millions of 1987 dollars discounted from 1998; discount rate: 2 %.

[b]DD- delay disposal, in years.

## B. Discussion

Before comparing the results of the economic analysis for the different repository media and the different back end cycles considered, a discussion on important items is presented below. These items include the transportation costs, linked to MRS facility and repository locations, the borehole drilling costs, the overpack costs,

TABLE 30. Sensitivity analysis in tuff (350 m), HLW-4020

| Parameter | Reference Cost[a] | DD | PARAMETER SETTING High Cost | Change % | DD | Low Cost | Change % | DD |
|---|---|---|---|---|---|---|---|---|
| FIXED DISPOSAL SCHEDULE | | | | | | | | |
| Discount rate | 3,318 | 5 | 2,664 | -19.7 | 5 | 4,353 | +31.2 | 5 |
| Backfill delay | | | 3,796 | +14.4 | 5 | | | |
| Surf. cap. cost | | | 3,455 | +4.1 | 5 | 3,250 | -2.1 | 5 |
| MRS capital cost | | | 3,509 | +5.8 | 5 | 3,152 | -5.0 | 5 |
| Surf. oper. cost | | | 3,416 | +3.0 | 5 | 3,220 | -3.0 | 5 |
| MRS oper. cost | | | 3,488 | +5.1 | 5 | 3,148 | -5.1 | 5 |
| Other oper. costs | | | 3,390 | +2.2 | 5 | 3,245 | -2.2 | 5 |
| Shaft contruc. | | | 3,336 | +0.5 | 5 | 3,299 | -0.6 | 5 |
| A-E cost | | | 3,380 | +1.9 | 5 | | | |
| Room length | | | 3,241 | +2.3 | 5 | | | |
| Other | | | | ≤ 1.0 | 5 | | ≤ 1.0 | 5 |
| VARIABLE DISPOSAL SCHEDULE | | | | | | | | |
| Discount rate | 3,318 | 5 | 2,452 | -26.1 | 30 | 4,353 | +31.2 | 5 |
| Backfill delay | | | 3,763 | +13.4 | 11 | | | |
| MRS capital cost | | | 3,509 | +5.8 | 5 | 3,077 | -7.3 | 22 |

[a]Costs in millions of 1987 dollars discounted from 1998; discount rate: 2%.

and possible cost reductions by slightly modifying the reference repository design.

## 1. Discussion of special cost issues

a. Facility location and transportation costs  The difference in storage plus disposal costs among different repository media are never very large, as shown in the results tables in the previous

TABLE 31. Sensitivity analysis in tuff (350 m), FHLW-5020

| Parameter | Reference Cost[a] | DD | PARAMETER SETTING High Cost | Change % | DD | Low Cost | Change % | DD |
|---|---|---|---|---|---|---|---|---|
| FIXED DISPOSAL SCHEDULE | | | | | | | | |
| Discount rate | 3,741 | 5 | 2,899 | -22.5 | 5 | 5,301 | +41.7 | 5 |
| Backfill delay | | | 3,894 | +4.1 | 5 | | | |
| Surf. cap. cost | | | 3,875 | +3.6 | 5 | 3,674 | -1.8 | 5 |
| MRS capital cost | | | 4,043 | +8,1 | 5 | 3,465 | -7.4 | 5 |
| Surf. oper. cost | | | 3,856 | +3.1 | 5 | 3,626 | -3.1 | 5 |
| MRS oper. cost | | | 3,928 | +5.0 | 5 | 3,556 | -5.0 | 5 |
| Shaft contruc. | | | 3,759 | +0.5 | 5 | 3,723 | -0.5 | 5 |
| A-E cost | | | 3,804 | +1.7 | 5 | | | |
| Others | | | | ≤ 1.0 | 5 | | ≤ 1.0 | 5 |
| VARIABLE DISPOSAL SCHEDULE | | | | | | | | |
| Discount rate | 3,612 | 30 | 2,433 | -32.6 | 30 | 5,301 | +46.8 | 5 |
| Backfill delay | | | 3,679 | +1.9 | 30 | | | |
| Surf. cap. cost | | | 3,694 | +2.3 | 30 | 3,571 | -1.1 | 30 |
| MRS capital cost | | | 4,043 | +11.9 | 5 | 3,043 | -15.8 | 30 |
| Surf. oper. cost | | | 3,682 | +1.9 | 30 | 3,542 | -1.9 | 30 |
| MRS oper. cost | | | 3,793 | +5.0 | 30 | 3,432 | -5.0 | 30 |
| A-E cost | | | 3,650 | +1.1 | 30 | | | |
| Others | | | | ≤ 1.0 | 30 | | ≤ 1.0 | 30 |

[a]Costs in millions of 1987 dollars discounted from 1998; discount rate: 2 %.

section. However, when the transportation costs are included, substantial differences appear for the different repository locations. The cost of transportation can, in some cases be higher than the storage and disposal costs, when the baseline cask leasing costs are used. Because of that it was chosen not to include the transportation costs in the results presented in the previous section. Furthermore, the transportation costs are not affected by most of the parameters that exert influence on storage or disposal costs; only the discount rate and the location of the facilities alter the transportation costs.

It must be recalled that two different transportation phases can take place if the MRS is not co-located with the repository. The first part involves the transportation of the unconsolidated spent fuel to the MRS location, and its cost is to be met by the utilities. The second transportation, for which the DOE is responsible, is from the MRS to the repository, if the two facilities are not co-located. The costs for the two operations are therefore given separately in Table 32, and for different discount rates. In the case of an MRS facility in Tennessee, two options for the second transportation phase are listed; for unconsolidated and consolidated spent fuel.

From a utility standpoint, it would be preferable to have the MRS located in Tennessee, closer to most of the reactor sites. If the MRS facility is not co-located with the repository, the distinction between consolidated or unconsolidated spent fuel from the MRS to the repository is very important. Indeed, if consolidation takes place in the MRS, as it is currently being planned, the total transportation charges can be lower for the scenario of the MRS in Tennessee than for an MRS co-located. In the particular cases of the repository being located in basalt or tuff, locating the MRS away from the repository site, if the transportation casks are leased at the estimated baseline costs, a net savings of over $100 M (1987 dollars) would result for the reference case of a discount rate of 2 %; over $300 M saved in

TABLE 32. Total transportation costs

| Transportation | Spent fuel form | DR[a]:0 Cost[b] | DR:2% Cost | DR:4% Cost |
|---|---|---|---|---|
| MRS in TENNESSEE | | | | |
| Reactors to MRS | Unconsolidated | 2,736 | 2,034 | 1,559 |
| MRS to basalt rep. | Unconsolidated | 5,543 | 2,732 | 2,596 |
| | Consolidated | 1,868 | 1,258 | 875 |
| MRS to salt rep. | Unconsolidated | 2,736 | 1,842 | 1,282 |
| | Consolidated | 924 | 622 | 433 |
| MRS to granite rep | Unconsolidated | 2,736 | 1,842 | 1,282 |
| | Consolidated | 924 | 622 | 433 |
| MRS to tuff rep. | Unconsolidated | 4,996 | 3,364 | 2,340 |
| | Consolidated | 1,684 | 1,134 | 789 |
| MRS CO-LOCATED WITH REPOSITORY | | | | |
| Reac. to salt rep | Unconsolidated | 3,506 | 2,606 | 1,998 |
| Reac.-granite rep | Unconsolidated | 3,506 | 2,606 | 1,998 |
| Reac. - basalt rep | Unconsolidated | 5,179 | 3,850 | 2,951 |
| Reac. to tuff rep | Unconsolidated | 4,905 | 3,646 | 2,795 |

[a]DR- dicount rate.

[b]Costs in millions of 1987 dollars discounted with respect to the year 1998.

transportation and $200 M of cost increase in repository facilities. This figure, however, is for the total back end cycle cost; in fact, when two different counts are made, one for the utilities and a second for the DOE charges, not co-locating the MRS with the repository results in savings between $600 M and $1,800 M for the utilities, but adds an additional cost between $800 M and $1,500 M for the Department of Energy.

A rather different picture can be seen if, instead of estimating the transportation costs under the assumption that the casks are leased, it is assumed that the transportation casks are bought. In calculating the costs produced by the alternative of purchasing the casks, the transportation charges have been divided into cask costs and freight charges, the latter maintained at the same values as for the baseline case. Information about the manufacturing cost of the reference IF-300 transportation casks exists (33,63,80), and the most conservative estimate has been selected (63). The cost of purchasing an IF-300 cask, properly escalated to 1987 dollars is taken as $6.3 M, to which a 10 % surcharge is added to cover quality assurance, licensing, and delivery fees. An arbitrary cost of $5,000/shipment (1987 dollars) is assumed, in order to cover maintenance and inspection operations.

Under the assumed scenario of 1310 MTHM/year during the first 5 years and 2620 MTHM/year for the other 25 years of operations, the number of shipments is calculated at 406 shipments/year from 1998 to 2002, and 812 shipments/year from 2002 to 2028, for the transportation from reactors to the MRS facility. When the MRS in not co-located, transportation of consolidated spent fuel from the MRS to the disposal site would require 136 shipments/year for 5 years and 272 shipments/year the following 25 years. To be consistent with the calculation of cask leasing fees, the purchased casks are assumed to be in use 292 days per year, and the same average speed of 75 miles per day (round-trip) is assumed in calculating the number of days required per shipment. Two additional days per shipment are necessary for loading/unloading operations. With this information, the distance between the different locations, and the assumption that the lifetime of the transportation casks is about 15 years, the number of casks and their cost have been estimated. The baseline value of 2 % has been assumed for the discount rate.

As an example, the estimate of cask purchasing for transporting the spent fuel from the reactors to an MRS located in Tennessee, is calculated as follows:

Average distance from reactors to MRS: 1,100 miles.

Average number of days required per shipment: 17 days.

Number of shipments that one cask can complete annually (292 days of use): 17 shipments/year.

The number of casks required and their costs, properly discounted:

24 casks required in 1998: $ 166 M

24 casks added in 2003 : $ 151 M

24 casks replaced in 2013: $ 124 M

24 casks replaced in 2018: $ 112 M

Maintenance and inspection: $ 83 M

TOTAL : $ 636 M

The same procedure has been used in all possible transportations considered. The results and comparison of cask purchasing with cask renting costs are shown in Table 33. For transporting spent fuel from the MRS to the disposal location, if different, only consolidated spent fuel has been considered.

TABLE 33. Transportation cost comparison for cask leasing/purchasing

| | Millions of 1987 dollars; discount rate:2 % | | | | |
|---|---|---|---|---|---|
| Transportation | Casks cost | Freight charges | Total purchasing | Cask leasing | Savings |
| MRS CO-LOCATED WITH REPOSITORY | | | | | |
| Reac.-salt rep | 820 | 785 | 1,605 | 2,606 | 1,001 |
| Reac.-granite rep | 820 | 785 | 1,605 | 2,606 | 1,001 |
| Reac.-basalt rep | 1,257 | 1,034 | 2,291 | 3,850 | 1,559 |
| Reac.-tuff rep | 1,119 | 996 | 2,115 | 3,646 | 1,531 |
| MRS NOT CO-LOCATED WITH REPOSITORY | | | | | |
| Reac. to MRS | 636 | 654 | 1,290 | 2,034 | 744 |
| MRS to salt rep | 175 | 206 | 381 | 622 | 241 |
| MRS - granite rep | 175 | 206 | 381 | 622 | 241 |
| MRS to basalt rep | 388 | 341 | 729 | 1,258 | 529 |
| MRS to tuff rep | 345 | 317 | 662 | 1,134 | 472 |

The total transportation costs are much lower when the alternative of purchasing the casks is considered. The utilities are the parties that can take more advantage of purchasing the transportation casks rather than renting them. Of course, several utilities might have to share a cask in order to maintain its usage at about 292 days per year; otherwise, the option of purchasing the casks would not result in large cost reductions. When the MRS is not co-located with the repository, the DOE can also obtain considerable savings by purchasing instead of renting the transportation casks, as seen from the table. Considering again that not co-locating the MRS with the repository increases the repository facilities cost by about $200 M, siting the MRS in Tennessee no longer results in a net cost reduction when the transportation casks are bought.

In summary, it has been seen that buying the transportation casks instead of leasing them results in considerable savings for the back end cycle as a whole, and for the utilities and the DOE in particular. Analyzing only the costs incurred by the DOE, locating the MRS in the disposal site results in eliminating transportation costs, but this solution would be more expensive for the utilities. Considering the entire back end of the fuel cycle as a single system, when the transportation casks are leased, siting the MRS away from the repository results in lower system costs if the disposal sites are very far from the MRS location (basalt, tuff) and consolidation takes place in the MRS facility; on the other hand, higher costs result for a closer repository location (salt, granite). However, when the transportation casks are purchased, the total system costs are quite insensitive to whether the MRS is co-located with the repository or is in Tennessee, with a slight preference for co-location (salt, granite, tuff).

It is clear from the estimated transportation costs that if the MRS is in Tennessee, consolidation at the MRS greatly reduces the system cost. For an MRS co-located, consolidation before storage is also preferred for the once-through cycle, because of the reduction in storage costs. Furthermore, even in a reprocessing cycle in which the spent fuel does not have to be necessarily consolidated, consolidation expenses are compensated by the decrease in storage cost. The maximum penalty for consolidating the spent fuel in a co-located MRS facility before storage has been estimated at $6 M.

b. Borehole drilling and overpack costs It was pointed out in Chapter V that these were two rather expensive operations and that any alternative method to reduce their cost would have a considerable impact in the total disposal expenses. In hard rocks in particular, borehole drilling represents in some cases as much as 18 % of the total repository costs. Similarly, the cost of the Ti-clad overpacks can easily amount to 20 % of the repository costs, this percentage becoming higher for canisters containing low amounts of waste, i.e., SF canisters for 3 assemblies, or HLW-3010 canister type.

The borehole drilling costs as in the baseline case are about $2,000/m of depth in hard rock, which would correspond to about 50 manhours, or 2 persons working an 8-hour shift during 3 days. It is difficult to estimate an alternative cost without precisely defining the alternative drilling method to be used. For the purposes of this study, it will be assumed that a method based on sawing the rock between small drill holes can be developed so as to reduce the manpower requirements to 1/3 of the reference; that is, 2 persons working an 8-hour shift could drill 1 m of depth in one day. Using this reduction factor in the borehole drilling costs results in cost estimates in the range of the values given in an alternative literature source (7) for basalt. For consistency, the drilling costs in other rocks are also reduced by a factor of 3, which for tuff, would give a value in the neighborhood of that estimated in reference 126.

To calculate a cost reduction factor for the overpacks, it is assumed here that the overpack design is changed. Assuming that the thick carbon steel overpack is not necessary for structural integrity of the canister, the canister/overpack design could be the same for all repository media. Also, a possible alternative design, if Ti is still desired for corrossion resistance, would be to build the canister directly with Ti, instead of having a stainless steel canister, a carbon steel reinforcement, and a Ti overpack. Under the assumption of this alternate design, data for non Ti-overpacked package designs (53,127) and the canister cost data used for hulls/hardware and Cs/Sr waste, have been used to estimate the cost reduction with respect to the reference overpack designs. Since the cost estimates from those references were for steel canisters instead of Ti, it has been assumed that a Ti canister could cost twice as much as a steel canister, for conservatism. With this conservative approach, the cost of Ti canisters to substitute for the carbon steel/Ti overpacks, would be about 1/2 of the reference cost for the tuff design and 1/3 for disposal in other media.

Under these assumptions, the storage plus disposal costs with the alternative drilling and overpack costs have been re-calculated. Only the reference canister sizes in each host rock have been studied, and always using the baseline discount rate of 2 %. The results and the potential savings obtained by the alternative costs discussed are shown in Table 34.

Naturally the savings in drilling costs that could be obtained are more important for hard rocks. The potential savings would also be more substantial for a once-through cycle, since SF disposal (with the reference canister types selected) would require a larger number of (deeper) boreholes when compared to HLW disposal. Although a FHLW scheme requires more borehole drilling, the savings are lower with respect to SF because a substantial number of them are drilled with a 30-year delay and have a smaller diameter (Cs/Sr disposal boreholes).

If the overpack costs can be made lower, the savings attained would affect principally the SF disposal, which is the cycle requiring more and larger overpacks. FHLW is less affected by a cost reduction in overpacks than HLW, because a FHLW cycle requires only 89 % of the overpacks needed in a HLW cycle for equal canister sizes. In the present analysis, the number of canisters in the FHLW scheme is further reduced by the use of a larger canister size. Although the cost

TABLE 34. Storage plus disposal costs with alternative drilling costs and overpacks

| Host Rock | Waste form | Canister type | Reference costs | With lower drilling costs | Savings | With new Ti canisters | Savings |
|---|---|---|---|---|---|---|---|
| SALT | SF | 6a/c | 4,179[a] | 4,105 | 74 | 3,833 | 175 |
| | HLW | 4020 | 3,377 | 3,324 | 74 | 3,833 | 348 |
| | FHLW | 5020 | 3,894 | 3,839 | 55 | 3,767 | 127 |
| GRANITE | SF | 6 a/c | 4,020 | 3,868 | 152 | 3,672 | 348 |
| | HLW | 4020 | 3,490 | 3,385 | 105 | 3,328 | 162 |
| | FHLW | 5020 | 3,962 | 3,848 | 114 | 3,830 | 127 |
| BASALT | SF | 6 a/c | 4,435 | 4,276 | 159 | 4,087 | 348 |
| | HLW | 4015 | 3,922 | 3,797 | 125 | 3,711 | 211 |
| | FHLW | 5020 | 4,108 | 3,997 | 114 | 3,981 | 127 |
| TUFF | SF | 6 a/c | 3,698 | 3,624 | 74 | 3,523 | 175 |
| 350 m | HLW | 4020 | 3,318 | 3,265 | 53 | 3,244 | 74 |
| | FHLW | 5020 | 3,741 | 3,686 | 55 | 3,674 | 67 |
| TUFF | SF | 6 a/c | 3,670 | 3,596 | 74 | 3,495 | 175 |
| 700 m | HLW | 4020 | 3,309 | 3,256 | 53 | 3,235 | 74 |
| | FHLW | 5020 | 3,831 | 3,776 | 55 | 3,764 | 67 |

[a]Costs in millions of 1987 dollars discounted with respect to the year 1998; discount rate: 2%.

reduction in tuff appears to be smaller than in other rocks, this is due to the fact that the original overpack design was thinner (and less costly) for a repository in tuff, and the overpack cost was already lower in the reference case.

c. Changes in repository design There are two changes in the repository design that could help reduce the cost of disposal, namely the reduction in number of shafts, and modifying the emplacement of SF hardware and cladding hulls. The reference design for HLW/FHLW includes an additional shaft with respect to a design for SF disposal, to handle the low-level-waste and hardware/hulls. The number of canisters to be emplaced per day, however, is never very large, and it is reasonable to assume that the main waste shaft could be used to handle the transfer of LLW and ILW to the underground facility. Although the savings are not spectacular, the elimination of the LLW shaft in HLW/FHLW cycle would result in a cost reduction of:

| | | |
|---|---|---|
| SALT | - | \$ 35 M (1987 dollars) |
| GRANITE | - | \$ 18 M |
| BASALT | - | \$ 35 M |
| TUFF (350 m) | - | \$ 11 M |
| TUFF (700 m) | - | \$ 22 M |

The cost reductions given correspond to the default schedule for disposal operations (starting in 2003), and if the disposal is further delayed, the savings would be discounted. It must also be pointed out that if it is possible to reduce the number of shafts, the integrity of the geologic media is improved, for less intrusions and rock disturbances are created. The possibility of using the waste shaft, for example, as the air intake shaft in any design, could be investigated, not only for the possible savings in shaft construction costs, but also to keep the rock disturbance at a minimum.

An additional change in the repository design would affect the emplacement of the SF hardware, and cladding hulls in the reprocessing cycles. In the reference design, these waste forms are emplaced in drilled boreholes. However, the radioactivity levels and heat generation rates for this type of waste are relatively low, especially under the contemplated scenarios, in which waste younger than 16 years is never disposed. Because of this, an alternative emplacement method would be to pile up the hardware/hulls canisters in excavated rooms, as it is to be done with the TRU drums in the reference design. To calculate the cost reduction that could be achieved with this emplacement method, it has been assumed that the equivalent of 6, 4 m long, canisters could be horizontally piled in a 3x3 m disposal room. The assumed emplacement cost is $400 per 1, 4 m long, canister (or the equivalent 3, 1.3 m long, canisters), corresponding to about 10 manhours.

The potential savings using the alternative hardware/hulls emplacement method would be higher for the HLW/FHLW cycles than for a SF disposal cycle (cladding hulls are not separated in a once-through cycle). Under the default disposal schedule of operations, and with a discount rate of 2 %, the estimated cost reduction would range from about $ 35 M (1987 dollars) for SF disposal in salt and tuff, to about

$ 85 M for HLW/FHLW disposal in the same media; for hard rocks, the corresponding values would be $ 55 M for SF disposal and $ 130 M for HLW/FHLW cycles.

## 2. Comparative summary of geologic formations

The purpose of this section is to compare the results of the economic analysis for the different host rocks. Two cases must be differentiated when comparing the proposed repository media; first, the differences in disposal costs from formation to formation that are intrinsic to the geologic media; second, since the locations for possible repositories in several media have been identified, a comparison of host rocks can include not only the intrinsic effects of the rock characteristics, but also the location, which is very important given the expensive transportation operations.

The results for the different repository media are summarized in two tables, Table 35, in which only the storage plus disposal costs are listed, and Table 36, where the DOE transportation costs are included. In other words, the first table lists DOE's costs (storage plus disposal) when the MRS is co-located with the repository. Because no transportation charges are included here, the differences in cost estimates depend upon the characteristics of the rocks, but not on their location. The second table presents DOE costs under the assumption that the MRS is located in Tennessee, so that transportation charges from the MRS to the repository site are included, and the differences among host rocks depend also on the repository location.

TABLE 35. Summary of costs for different repository media, MRS at disposal site

| | BACK END FUEL CYCLE | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Spent Fuel disposal | | | | | | High-Level Waste disposal | | | | | | Fractionated Waste disposal | | | | | |
| | Reference | | Maximum | | Minimum | | Reference | | Maximum | | Minimum | | Reference | | Maximum | | Minimum | |
| | Cost | DD[b] | Cost | DD | Cost | DD | Cost | DD | Cost | DD | Cost | DD | Cost | DD | Cost | DD | Cost | DD |
| FIXED DISPOSAL SCHEDULES | | | | | | | | | | | | | | | | | | |
| SALT | 4179 | 5 | 5133 | 5 | 3206 | 5 | 3377 | 5 | 4202 | 5 | 2548 | 5 | 3894 | 5 | 4823 | 5 | 2951 | 5 |
| GRANITE | 4020 | 5 | 4836 | 5 | 3364 | 5 | 3490 | 5 | 4286 | 5 | 2870 | 5 | 3962 | 5 | 4873 | 5 | 3219 | 5 |
| BASALT | 4435 | 5 | 5288 | 5 | 3720 | 5 | 3922 | 6 | 4787 | 6 | 3236 | 6 | 4108 | 5 | 5063 | 5 | 3346 | 5 |
| TUFF[c] | 3698 | 5 | 4493 | 5 | 3050 | 5 | 3318 | 5 | 4089 | 5 | 2701 | 5 | 3741 | 5 | 4632 | 5 | 3018 | 5 |
| VARIABLE DISPOSAL SCHEDULE | | | | | | | | | | | | | | | | | | |
| SALT | 4179 | 5 | 5133 | 5 | 3052 | 30 | 3377 | 5 | 4202 | 5 | 2548 | 5 | 3706 | 30 | 4823 | 5 | 2642 | 30 |
| GRANITE | 4020 | 5 | 4836 | 5 | 3149 | 30 | 3490 | 5 | 4286 | 5 | 2857 | 30 | 3744 | 30 | 4873 | 5 | 2805 | 30 |
| BASALT | 4350 | 17 | 5288 | 5 | 3303 | 30 | 3913 | 9 | 4787 | 6 | 2990 | 30 | 3832 | 30 | 5063 | 5 | 2879 | 30 |
| TUFF | 3698 | 5 | 4493 | 5 | 2908 | 30 | 3318 | 5 | 4089 | 5 | 2680 | 11 | 3612 | 30 | 4632 | 5 | 2682 | 30 |

[a]Costs in millions of 1987 dollars discounted with respect to the year 1998; discount rate: 2%.

[b]DD delay of disposal, in years.

[c]Values given are for shallow tuff. Results for deep tuff are less than 1 % different.

One thing that must be mentioned is that only one set of values has been entered in the tables for a repository in tuff. This is because the costs for the two possible repository depths were very close, with differences of less than 1 % in all cases except in the FHLW cycle, where the variations were between 1 and 2 percentage points. The difference between the two repositories is in the shaft construction costs, partially compensated by the higher permissible thermal loadings in the deeper horizon repository. For FHLW, there is no difference in thermal loadings because the minimum pitch can always be used; thus, the difference is only in the shaft construction costs, slightly above 1 %.

The results shown in the first table are discussed first, and correspond to the applicable case if the MRS is co-located with the repository. Basalt appears to be the medium that would result in the highest storage and disposal costs, and this is due to the higher excavation costs and more restricted thermal loadings. The two factors come together in a repository in basalt: large excavation volumes and large unit excavation costs. Granite or salt follow basalt, depending on the cycle selected; for the once-through cycle, the excavation volumes in salt are very large (very restrictive FF thermal loading for SF disposal) and, regardless of the low unit excavation cost in salt, the total mining costs are higher than in granite. For a reprocessing cycle, however, for which the FF salt thermal loading is not so severely restricted, the excavation volumes in salt are comparable to those in granite and the total mining costs are higher in granite,

TABLE 36. Summary of costs for different repository media, MRS in Tennessee

| | BACK END FUEL CYCLE | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Spent Fuel disposal | | | | | | High-Level Waste disposal | | | | | | Fractionated Waste disposal | | | | | |
| | Reference | | Maximum | | Minimum | | Reference | | Maximum | | Minimum | | Reference | | Maximum | | Minimum | |
| | Cost | DD[b] | Cost | DD | Cost | DD | Cost | DD | Cost | DD | Cost | DD | Cost | DD | Cost | DD | Cost | DD |
| FIXED DISPOSAL SCHEDULES | | | | | | | | | | | | | | | | | | |
| SALT | 4796 | 5 | 5821 | 5 | 3960 | 5 | 3816 | 5 | 4664 | 5 | 3168 | 5 | 4337 | 5 | 5290 | 5 | 3573 | 5 |
| GRANITE | 4637 | 5 | 5585 | 5 | 3895 | 5 | 3929 | 5 | 4780 | 5 | 3279 | 5 | 4400 | 5 | 5341 | 5 | 3652 | 5 |
| BASALT | 5400 | 5 | 6458 | 5 | 4550 | 5 | 4693 | 6 | 5644 | 6 | 3955 | 6 | 4900 | 5 | 5884 | 5 | 4123 | 5 |
| TUFF[c] | 4597 | 5 | 5531 | 5 | 3858 | 5 | 4038 | 5 | 4484 | 5 | 3378 | 5 | 4466 | 5 | 5383 | 5 | 3732 | 5 |
| VARIABLE DISPOSAL SCHEDULE | | | | | | | | | | | | | | | | | | |
| SALT | 4570 | 30 | 5821 | 5 | 3507 | 30 | 3816 | 5 | 4664 | 5 | 3007 | 30 | 3974 | 30 | 5157 | 30 | 3019 | 30 |
| GRANITE | 4475 | 30 | 5585 | 5 | 3469 | 30 | 3929 | 5 | 4780 | 5 | 3063 | 30 | 4013 | 30 | 5187 | 30 | 3066 | 30 |
| BASALT | 4866 | 30 | 6155 | 30 | 3817 | 30 | 4415 | 30 | 5621 | 11 | 3450 | 30 | 4313 | 30 | 5513 | 30 | 3352 | 30 |
| TUFF | 4392 | 30 | 5531 | 5 | 3406 | 30 | 4020 | 10 | 4484 | 5 | 3095 | 30 | 4052 | 30 | 5212 | 30 | 3115 | 30 |

[a]Costs in millions of 1987 dollars discounted with respect to the year 1998; discount rate: 2%.

[b]DD delay of disposal, in years.

[c]Values given are for shallow tuff. Results for deep tuff are less than 1 % different.

given the much higher unit excavation cost in this hard rock. Construction of a repository in a tuffaceous formation yields the lowest storage plus disposal costs, for tuff combines relatively high permissible thermal loadings with moderate unit excavation costs.

In evaluating the quantitative differences among the several rocks, one must distinguish between the scenario with fixed disposal schedules and the possibility of reducing costs by delaying the commencement of disposal operations. If no delay beyond the year 2003 is allowed for starting waste disposal, disposal in tuff would result in storage plus disposal costs between $170 M and $340 M lower than disposal in granite, depending on the cycle and the unit costs. The cost reduction with respect to salt would range between $200 M and $640 M for a once-through cycle, or between 0 and $200 M for a reprocessing cycle. Basalt yields storage plus disposal costs between $320 M and $740 M above those for disposal in tuff.

When optimization with respect to the period of storage is permitted, the differences between rocks decrease in some instances. Disposal in basalt is still the most expensive alternative and a repository in tuff is still the best choice. Although the upper bounds of the costs are still the same, and thus the maximum possible differences between disposal in different rocks remain unaltered, the baseline cost values for basalt in any cycle and for all rocks in the FHLW cycle are reduced by delaying disposal.

The benefits obtained by delaying disposal depend on both the fuel cycle and the repository medium. Results for a repository in basalt indicate that there is a cost reduction if disposal is delayed regardless of the waste form disposed. This happens only in basalt because of the more restrictive thermal loadings, which result in large excavation volumes and costs; aging the waste before disposal represents a significant decrease in mining costs, which more than offset the increase in storage costs. Note also that the optimum period of storage for SF, with higher heat generation, is 17 years, whereas it is only 9 for HLW. Nevertheless, when the storage cost components are very high, as in the case of the upper bound of the cost estimates, delaying disposal never results in a final cost reduction.

Using the baseline cost estimates, delaying disposal operations in a FHLW cycle produces between \$190 M and \$280 M in savings, depending on the host rock. In other words, with a fractionated waste cycle, starting disposal operations after 5 years of storage instead of 30 adds a penalty of \$190 M to \$280 M. For other cycles, early disposal in basalt also represents a cost penalty, of only \$9 M for HLW disposal, and \$85 M for SF. For SF and HLW disposal in other rocks, the situation switches, and late disposal would be penalized instead. The extra amount for delaying disposal varies with host rock and cycle, and delay period. For example, for the case of starting disposal operations in 2013, a disposal delay of 15 years, the extra cost would range from \$101 M in tuff and SF, to \$60 M in granite and SF.

If the scenario is for an MRS located in Tennessee, transportation cost from MRS to the disposal site must be added to the DOE costs, along with the additional expenses of a second waste receiving facility in the repository location. The differences in total costs (Table 36) for different geologic formations depend now on the location of the possible disposal site. A repository in basalt, the furthest location from the MRS, is at a still larger disadvantage with respect to the other formations. The differences between a repository in tuff or one in granite or salt are no longer very significant, for the intrinsic differences that appeared among the three media are now compensated by their location (the proposed repository in tuff is much farther from the MRS than those in salt and granite).

Comparing baseline cost differences between different formations, with a fixed storage period of 5 years, the range is between \$390 and \$810 M for tuff with respect to basalt. The differences between tuff and granite or salt depend on the cycle; for SF disposal, a repository in tuff is between \$40 and \$200 M cheaper than in the other rocks; for reprocessing cycles, salt is between \$130 and \$210 M less expensive than one in tuff, and disposal in granite is \$60 to \$110 M less expensive than disposal in tuff.

When the transportation costs and the additional waste receiving facility in the repository are included in the cost estimates, a new incentive for deferring disposal (deferring some of the costs) appears. Because of that, as can be seen in Table 36, more cases analyzed present the possibility of total cost reduction by delaying the disposal operations. This happens in all the baseline cases except disposal of HLW in salt or granite, where the default 5-year storage period is still the more economic solution. The reason for this behavior is that for HLW, very little is gained in the form of improving the density of disposal by aging the waste still further. It must be recalled that the waste, for 5 years of storage before disposal, has already been between 16 and 29 years out of the reactor. With SF, the benefits of a few more years of storage are more considerable and deferring disposal results in a net cost reduction for the system. In the FHLW cycle, although no gain exists in the form of density of disposal by further aging the waste, both the storage and disposal costs are incurred over a much longer period of time, and this makes deferral of disposal operations result in a cost reduction in most of the situations.

## 2. Comparative summary for the three back end cycles

The differences between the once-through and the two reprocessing cycles, from the economic point of view, are analyzed in this section. For comparing the differences in costs produced by selection of the three cycles considered, the transportation costs will not be included, since those should be the same regardless of the cycle (only SF transportation takes place from the MRS to the disposal site, since in the reprocessing cycles the reprocessing plant is co-located with the repository). Cost estimates assuming that the MRS is co-located with the repository are therefore used in the comparison. In fact, location of the MRS in Tennessee results in an increase of about $180 M in the total cost difference between the once-through and the reprocessing cycles. These additional $180 M correspond to the cost of the receiving facility of the repository, which is assumed to be part of the reprocessing plant.

The cost estimates for the different cycles are given in Table 37 for the different repository media, cycles, and the optimization options. The data in the table have been estimated under the assumptions that the two proposed changes in the reference repository design take place; that is, repositories for both SF and reprocessed waste have 4 shafts, and the SF hardware/cladding hulls are not emplaced in boreholes, only piled in the disposal rooms.

The results shown in the table indicate that the regular reprocessing cycle yields the lowest costs. The differences among the three cycles reside essentially in the excavation, borehole drilling, and canister emplacement costs, the cost components that are more sensitive to the number of canisters disposed. In the FHLW, where the mining-related expenses are at a minimum, the total costs are not drastically reduced with respect to the other two cycles because of the longer period of repository operations that is required. The largest difference between SF and HLW disposal occur for a repository in salt, which could be expected from the thermal analysis results indicating that the FF limit was considerably different for SF or reprocessed waste. The differences in cost between SF and HLW disposal for the other rocks are roughly proportional to the unit excavation costs in the corresponding media, which seems natural recalling that the difference between maximum permissible thermal loadings for SF and HLW disposal followed the same trend in all three rocks.

TABLE 37. Summary of costs for comparison of cycles

| | BACK END FUEL CYCLE | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Spent Fuel disposal | | | | | | High-Level Waste disposal | | | | | | Fractionated Waste disposal | | | | | |
| | Reference | | Maximum | | Minimum | | Reference | | Maximum | | Minimum | | Reference | | Maximum | | Minimum | |
| | Cost | DD[b] | Cost | DD | Cost | DD | Cost | DD | Cost | DD | Cost | DD | Cost | DD | Cost | DD | Cost | DD |
| FIXED DISPOSAL SCHEDULES | | | | | | | | | | | | | | | | | | |
| SALT | 4127 | 5 | 5096 | 5 | 3355 | 5 | 3255 | 5 | 4064 | 5 | 2633 | 5 | 3774 | 5 | 4686 | 5 | 3036 | 5 |
| GRANITE | 3957 | 5 | 4839 | 5 | 3271 | 5 | 3378 | 5 | 4156 | 5 | 2714 | 5 | 3808 | 5 | 4713 | 5 | 3084 | 5 |
| BASALT | 4403 | 5 | 5362 | 5 | 3576 | 6 | 3788 | 6 | 4663 | 6 | 3041 | 5 | 3979 | 5 | 4879 | 5 | 3188 | 5 |
| TUFF[c] | 3652 | 5 | 4560 | 5 | 2970 | 5 | 3212 | 5 | 4070 | 5 | 2599 | 5 | 3642 | 5 | 4563 | 5 | 2930 | 5 |
| VARIABLE DISPOSAL SCHEDULE | | | | | | | | | | | | | | | | | | |
| SALT | 4127 | 5 | 5096 | 5 | 3143 | 30 | 3255 | 5 | 4064 | 5 | 2633 | 5 | 3622 | 5 | 4686 | 5 | 2694 | 30 |
| GRANITE | 3957 | 5 | 4839 | 5 | 3093 | 30 | 3378 | 5 | 4156 | 5 | 2714 | 5 | 3653 | 30 | 4713 | 5 | 2723 | 30 |
| BASALT | 4328 | 16 | 5357 | 7 | 3227 | 30 | 3786 | 7 | 4663 | 6 | 2885 | 30 | 3754 | 30 | 4879 | 5 | 2785 | 30 |
| TUFF | 3652 | 5 | 4560 | 5 | 2869 | 30 | 3212 | 5 | 4070 | 5 | 2757 | 9 | 3551 | 30 | 4563 | 5 | 2629 | 30 |

[a]Costs in millions of 1987 dollars discounted with respect to the year 1998; discount rate: 2%.

[b]DD delay of disposal, in years.

[c]Values given are for shallow tuff. Results for deep tuff are less than 1 % different.

Comparing the once-through cycle with the fractionated reprocessing cycle, the differences, in favor of the FHLW scheme, are lower than the cost reductions achieved with HLW with respect to SF. Although the mining-related costs are even lower for FHLW, keeping the facilities operating for an extended period of time greatly reduces the potential savings to be achieved with the fractionated waste cycle. The heavier penalties of a SF cycle with respect to the FHLW take place again for salt and basalt, the more thermally restricted rocks for SF disposal. In granite, where the unit excavation costs are high, FHLW still produces a $150 M cost reduction with respect to SF, but the savings are almost negligible in tuff, which has reasonably high thermal loadings for SF and moderate unit excavation costs.

The ranges of potential cost reductions for selecting a regular reprocessing cycle over the once-through, are $872 M ($722 M to $1,032M) in salt, $615 M ($535 M to $699 M) for a repository in basalt, $579 M ($557 M to $683 M) in granite, and $440 M ($391 M to $540 M) for disposal in a tuff repository. The ranges given are for the fixed disposal schedule option; in the event of optimizing with respect to the storage period the lower bound is further reduced by about 30 %. The potential savings in the reprocessing cycle indicate that the reprocessing option would be economically preferable if the net expenses of reprocessing the spent fuel can be maintained below $12/KgHM ($10/KgHM to $14/KgHM) for disposal in salt or below approximately $8/KgHM ($5/KgHM to $10/KgHM) for disposal in other rocks. If it were decided to locate the MRS in Tennessee in the once-through cycle, \$2.5/KgHM can be added to these numbers. Existing estimates for reprocessing expenses are much higher than the values just given (5). However, in evaluating the average net expenses per unit weight of spent fuel reprocessed, several things must be taken into account. First, the average cutoff point given is per KgHM when the operating costs are discounted according to their schedule (the reference discount rate used here was 2 %). Secondly, the existing estimates are for plants designed to reprocess fresh spent fuel, whereas under the current scenario, spent fuel between 15 and 28 years old (or older, if disposal is further delayed) would be available for reprocessing. Furthermore, support facilities for the reprocessing plant would already exist in the repository, which could represent additional cost reductions in the reprocessing plant capital and operating cost estimates. Finally, the net reprocessing cost must be calculated after the revenues from selling the recovered actinides and, possibly, the noble metals have been subtracted from the expenses.

If the first disposal site is to be used for only the first 72,000 MTHM available for disposal, the FHLW would not be economically advantageous unless the reprocessing and solidification operations could be performed with a cost ranging from \$1/KgHM to \$7/KgHM, depending upon the repository medium. If the SF cycle has the MRS in Tennessee, \$2.5/KgHM should be added. The chance of the FHLW cycle to be economically competitive improves only slightly if the disposal is delayed beyond the year 2003. The possible renting fee for Cs should be considered in estimating the net cost. But the FHLW cycle presents one clear advantage over the SF disposal scheme; that is, because the thermal restrictions are never important for fractionated waste, the disposal surface area occupied in the repository is relatively small. Thus, in this scheme, the repository could be used to accommodate additional waste, beyond the initial 72,000 MTHM. For comparison, the disposal area used in a SF repository in salt is about 10 times larger than that used in FHLW disposal (including Cs/Sr disposal), 6 times larger for a repository in basalt, and about 3 times larger in the other two host rocks. If the same repository were to be used for additional waste, substantial savings would apply to the second scenario. Simply avoiding the land preparation, shaft construction, and preoperations for the second scenario adds over a $300 M in favor of the FHLW cycle. In summary, the FHLW cycle is not economically competitive with the other two schemes unless its effect on a second site is taken into account.

The results comparing the regular reprocessing cycle with the SF disposal cycle do not agree with a preliminary analysis (89), which indicated that the savings obtained by disposing HLW instead of SF could be between $900 M and $2,000 M (1984 dollars), with a mode around $1,500 M. The difference between the present analysis and the preliminary study resides mainly in the assumption in the latter of disposal of unconsolidated spent fuel. Furthermore, the previous study considered a maximum temperature limit of 200 °C for the spent fuel waste form, instead of the 375 °C limit used in the present work; this higher temperature limit is associated with consolidated fuel.

# VII. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

The twofold objective of the project has been accomplished; both the thermal and economic models for radioactive waste disposal have been developed and used in a parametric analysis. The thermal and economic studies have been carried out in such a way as to permit a comparison of the four geologic formations proposed for hosting a nuclear waste repository, and a comparison of three different models for the back end of the fuel cycle. Furthermore, the economic analysis has been performed under the expected scenarios and political constraints applicable to the first disposal site. This chapter summarizes the most important conclusions obtained from both models and suggests areas of possible further research, based on the observed economic effect produced by some of the parameters involved in the analysis.

## A. Conclusions from the Thermal Analysis

The thermal model has been divided into three ranges, the Very-Near-Field, the Near-Field, and the Far-Field, each with a different dimensional span and a different set of restrictions. The three fields have been decoupled to perform the parametric analysis and later linked together in order to determine the permissible thermal loadings under the simultaneous application of the three sets of restrictions. Aside from comparing the waste forms and the host rocks, the most important parameters considered in the model have been the age of the waste at emplacement, and the canister dimensions and waste content.

In the VNF range it was found that the bentonite buffer surrounding the canister becomes the thermal restriction, except for disposal of canisters with a very high heat generation rate, such as SF canisters containing 12 consolidated assemblies or 50 cm-diameter HLW canisters with a 20 % waste oxide concentration in the glass. In those cases the maximum acceptable temperature in the waste form sets the heat loading limit; as a result, the VNF thermal loading is more restrictive for SF than for reprocessed waste. These high-thermal-load waste forms can only be disposed after a relatively long period of cooling, which becomes longer for host rocks with lower thermal conductivity, such as basalt.

The effect of an air gap surrounding the canister with the purpose of facilitating the emplacement and (possible) retrieval operations has also been analyzed. Air gap thicknesses between 1 and 5 cm should be avoided, for they result in equivalent thermal conductivities below that of a bentonite buffer of equal size. An optimum air gap size of 6 cm was determined as a compromise between providing sufficient clearance for emplacement operations and keeping the borehole drilling costs to a minimum, while maintaining the equivalent thermal conductivity above that of the bentonite. A 6-cm air gap, in fact, slightly improves the heat transfer from the waste canister to the rock media, for the increased heat transfer surface area offsets the introduction of an additional temperature drop.

The Near-Field permissible thermal loadings were found to be dependent on the thermal properties of the host rock, and the restrictions become more severe as the thermal conductivity or the specific heat of the host rock decrease. Disposal of HLW, with a lower heat generation rate and a faster decay of the heat source when compared to spent fuel, results in higher permissible densities of disposal in all media. Increasing the room-to-room distance showed a slightly negative effect on the NF allowable loading. The NF loading for HLW appeared to be essentially dependent on the total heat emplaced per borehole, a combination of canister size, waste concentration, and age at disposal. However, for SF the situation becomes a two-parameter system, depending on both canister size and age at disposal. From the NF results, salt would appear to be the best medium, while basalt would be the most restricted.

The results of the FF range reverse the conclusions of the NF as far as salt being the best choice. The FF permissible loading, based on a maximum surface uplift criterion, proves to be more restrictive for rocks with higher thermal expansion coefficients, i.e., salt formations. Permissible loadings for SF disposal are again lower than those for HLW under the FF criteria. An increase in the repository depth results in a slight reduction in the acceptable FF loading.

When combining the permissible loadings from the VNF-NF fields with those from the Far-Field, the latter always dominates disposal in a repository in salt, regardless of the waste form. Disposal of HLW in other rocks is restricted only by the NF thermal loadings for ages at disposal ranging from 10 to 100 years. The maximum thermal loading for disposal of SF in shallow tuff is also determined by the NF restrictions alone. A combination of the NF and FF restrictions (depending upon the age at disposal) applies for the disposal of SF in granite, basalt, and deep tuff; the FF dominates for long-cooled fuel, and the NF otherwise.

After merging the results from the three thermal analysis ranges, permissible thermal loadings are always better for HLW. For SF, canisters containing 6 assemblies seem to be the best choice as a compromise between total number of canisters and thermal restrictions. For HLW disposal, granite is the rock formation with the highest acceptable loadings, followed by tuff (deep tuff slightly better than shallow), salt, and finally basalt. If SF is to be disposed, the thermally preferable medium is again granite, followed by tuff, then basalt, and salt in the last position.

A final conclusion refers to the effect of aging the waste before disposal; the mass loading in the repository monotonically increases with age at disposal, more so for HLW because of its faster-decaying source. The optimum thermal loading ($w/m^2$), however, tends to decrease for disposal of very-long-cooled waste, the reason being that the heat source decays faster for young waste, but the decay is slower the older the waste is at disposal. This effect is naturally more pronounced in disposal of Spent Fuel.

## B. Conclusions from the Economic Analysis

The costs for the back end of the nuclear fuel cycle have been estimated for a variety of situations. The system costs include storage and disposal when the MRS facility is co-located with the repository, with transportation costs added if the MRS is located in Tennessee. Three possible fuel cycle schemes have been studied, and disposal in five possible repositories (salt, basalt, granite, shallow tuff, and deep tuff) have been compared.

A baseline set of costs were defined, as well as a reference set of dimensions for the different facilities involved in the back end cycle. A range has been estimated for the different costs based on the uncertainty band associated with the baseline costs and dimensional parameters. A sensitivity analysis has been carried out to obtain the response of the economic model under variation of some important parameters.

The first conclusions refer to the canister type selection. A large canister size results in lower overpack, borehole drilling and emplacement costs, so that large canisters are preferred as long as they meet the thermal loading criteria. The 6-assembly canister has been selected as the best choice for SF disposal in all host rocks; a smaller canister results in higher disposal costs, while a 12-assembly canister is thermally restricted in basalt and tuff, and although permissible in salt and granite, the resulting borehole pitch is too large. Similar reasoning led to the choice of a 40-cm diameter, 20 % waste concentration canister type for disposal of HLW in salt, granite and tuff, and for disposal in the more thermally restricted basalt the preferred type was a 40-cm diameter, 15 % waste concentration canister. The largest possible canister (50 cm diameter, 20 % waste concentration) is always the least-cost choice for FHLW disposal.

The storage plus disposal costs for the three reference canisters have been found for the baseline cases and their associated upper and lower bounds. This corresponds to a situation in which the MRS is co-located with the repository. Two sets of values were determined, depending on whether the disposal schedule was fixed or was permitted to be delayed for the purpose of obtaining a net cost reduction. Next, the same cases were analyzed under the assumption of an MRS located in Tennessee, where the system costs are composed of transportation, storage, and disposal. Table 38 lists the baseline results and their ranges under the different situations considered. The costs are given in 1987 dollars per KgHM.

When the MRS is co-located with the repository the variations among the different media are never very large, and they reflect the differences in rock characteristics. The least-cost situation corresponds to a repository in tuff, due to its good thermal loadings and moderate mining costs. The highest cost is for a repository in basalt, which combines low thermal loadings with high mining costs. In between, salt and granite compete for the second best choice, salt for HLW/FHLW (good thermal loadings and low mining costs), and granite for SF (high mining costs, but much better densities of disposal than salt).

When the MRS is located in Tennessee, the differences in costs for repositories in the various geologic formations reflect not only the intrinsic differences between rocks (thermal loadings, mining costs),

TABLE 38. Summary of costs for the different situations analyzed

| Host Rock | SF Cost ($/KgHM)[a] | HLW Cost ($/KgHM) | FHLW Cost ($/KgHM) |
|---|---|---|---|
| 1. MRS CO-LOCATED WITH REPOSITORY | | | |
| FIXED DISPOSAL SCHEDULE | | | |
| SALT | 58 (45 - 71) | 47 (35 - 58) | 54 (41 - 67) |
| GRANITE | 56 (47 - 67) | 48 (40 - 59) | 55 (45 - 68) |
| BASALT | 62 (52 - 73) | 54 (45 - 66) | 57 (46 - 70) |
| TUFF 350 m | 51 (42 - 62) | 46 (38 - 57) | 52 (42 - 66) |
| TUFF 700 m | 51 (42 - 62) | 46 (37 - 57) | 53 (43 - 66) |
| VARIABLE DISPOSAL SCHEDULE | | | |
| SALT | 58 (42 - 71) | 47 (35 - 58) | 51 (37 - 67) |
| GRANITE | 56 (44 - 67) | 48 (40 - 59) | 52 (39 - 68) |
| BASALT | 60 (46 - 73) | 54 (42 - 66) | 53 (40 - 70) |
| TUFF 350 m | 50 (42 - 62) | 46 (37 - 57) | 50 (37 - 66) |
| TUFF 700 m | 51 (41 - 62) | 46 (37 - 57) | 51 (38 - 66) |
| 2. MRS LOCATED IN TENNESSEE | | | |
| FIXED DISPOSAL SCHEDULE | | | |
| SALT | 67 (55 - 81) | 53 (44 - 65) | 60 (50 - 73) |
| GRANITE | 64 (54 - 76) | 55 (46 - 66) | 61 (51 - 74) |
| BASALT | 75 (63 - 90) | 65 (55 - 78) | 68 (57 - 82) |
| TUFF 350 m | 64 (54 - 77) | 56 (47 - 62) | 62 (52 - 75) |
| TUFF 700 m | 63 (53 - 76) | 56 (47 - 68) | 63 (53 - 76) |
| VARIABLE DISPOSAL SCHEDULE | | | |
| SALT | 63 (49 - 81) | 53 (42 - 65) | 55 (42 - 72) |
| GRANITE | 62 (48 - 78) | 55 (43 - 66) | 56 (43 - 72) |
| BASALT | 68 (53 - 85) | 61 (48 - 78) | 60 (47 - 77) |
| TUFF 350 m | 61 (47 - 77) | 56 (43 - 62) | 56 (43 - 72) |
| TUFF 700 m | 62 (48 - 76) | 57 (43 - 68) | 57 (44 - 73) |

[a]The unit costs have been calculated from total system costs in 1987 dollars discounted with respect to the year 1998; discount rate: 2%.

but also the effect of the location of the disposal site with respect to the MRS. A repository in basalt (State of Washington) is further at disadvantage, and the system cost is well above that for disposal in any other rock formation. The differences between the other media, however, are smoothed under these conditions, since tuff, the best choice in case of co-location of MRS and repository, is penalized by the longer distance between Clinch River and Yucca Mountain, as compared with the distances between a repository in salt or granite and the MRS. Because of the restrictive thermal loadings for SF, a repository in salt still has a slightly higher cost than disposal in granite, and the situation is reversed for HLW/FHLW cycles. Adding the transportation costs improves the chances of a cost reduction by delaying disposal, since more costs are deferred.

Delay of disposal for a FHLW cycle, regardless of the MRS location, is preferred unless the capital cost of the storage facility is very high. For the other cycles, the convenience of delaying disposal depends upon the location of the MRS and the capital cost of the MRS facility. With baseline cost estimates, delaying SF/HLW disposal in salt, granite or tuff, results in a cost penalty if the MRS is co-located with the repository. If the MRS is not co-located, there is only a penalty for delaying disposal of HLW in salt or granite.

In case of lower storage costs than the baseline value (used in calculating the lower bounds of the cost ranges) delaying disposal offers the possibility of reducing the total system costs, which is the reason for the reduction in the lower bound estimates for variable disposal schedules with respect to fixed schedules. The difference among the various rocks regarding the optimum period of storage is a direct result of the maximum permissible thermal loadings in the different formations; the higher the permissible loadings, the smaller the gain that can be obtained by delaying disposal. Even in the cases where a cost reduction is accomplished by aging the waste before disposal, the savings are always below $200 M (1987 dollars) except for disposal in basalt, where the benefits can be as high as $540 M (1987 dollars). The reason for this is that basalt has the more restrictive thermal loadings, and aging the waste represents an important reduction in excavation requirements. Because the waste is already long-cooled for the minimum delay of disposal, the other rock formations, with better thermal loadings than basalt, do not achieve a significant reduction in excavation volumes by aging the waste, and the only gain is in the deferral of the disposal costs, often offset by the increase in storage costs.

In comparing the three cycles proposed, regular reprocessing yields the lowest costs for storage and disposal, followed by the reprocessing cycle with waste fractionation, and the once-through cycle is associated with the highest disposal costs. The economic feasibility of a reprocessing cycle over the once-through would depend on the reprocessing/solidification expenses. If those are lower than the difference between HLW/FHLW and SF disposal, a reprocessing cycle would be preferred; otherwise, a once-through cycle yields lower total system costs. The differences in costs between HLW and SF disposal range between a minimum of \$390 M for a repository in tuff and MRS located at the disposal site to a maximum of \$1,200 M for a repository in salt and MRS located in Tennessee. The differences between a FHLW and a SF disposal cycle are lower, from \$100 M (repository in tuff; MRS co-located) to \$580 M (disposal in salt; MRS in Tennessee). The cost reduction from SF to reprocessed waste disposal is more significant in salt because this is the medium that presents the largest differences in densities of disposal from one cycle to the others. Although FHLW disposal results in smaller excavation volumes than HLW disposal, the savings achieved with the fractionation scheme are not as big because of the expenses of keeping the facilities operating for a longer time. The most important advantage of the FHLW cycle is in the smaller disposal surface utilized, a reduction with respect to SF disposal from a factor of 3 in tuff and granite to a factor of 10 in salt. Because of that, the capacity of the repository could be greatly increased in a FHLW cycle, and this would produce more substantial savings, applicable to the second scenario (the batch of waste for disposal after the initial 72,000 MTHM).

The sensitivity analysis has been performed for all rock types and back end cycles. A summary of the qualitative results is given in Table 39.

The three parameters that have a strong effect on the outcome of the economic model are the discount rate, the MRS capital cost, and the delay of backfilling. The discount rate is so important because of the time span involved in the totality of the operations. Its effect is

TABLE 39. Summary of sensitivity analysis

| | SENSITIVITY OF THE MODEL[a] | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | SALT | | | GRANITE | | | BASALT | | | TUFF | | |
| Parameter | SF | HLW | FHLW | SF | HLW | FHLW | SF | HLW | FHLW | SF | HLW | FHLW |
| Discount rate | VH | VH | VH | VH | VH | VH | VH | VH | VH | VH | VH | VH |
| Backfill delay | H | H | M | H | H | M | H | H | M | H | H | M |
| Surf. cap. cost | M | M | M | M | M | M | M | M | M | M | M | M |
| MRS capital cost | H | H | H | H | H | H | H | H | H | H | H | H |
| Surf. oper. cost | L | L | L | L | L | L | L | M | L | L | L | L |
| MRS oper. cost | M | M | H | M | M | M | H | M | M | M | H | H |
| Underground oper | L | L | VL | L | L | VL | L | L | VL | L | L | VL |
| Shaft construc. | L | L | L | VL | VL | VL | L | L | L | L | L | L |
| A-E cost | L | L | L | L | L | L | L | L | L | L | L | L |
| Room dimensions | L | VL | VL | L | VL | VL | L | L | VL | L | L | VL |
| Room-room dist. | L | VL | VL | VL | VL | VL | L | VL | VL | VL | VL | VL |
| Rep. depth | L | VL | VL | VL | VL | VL | VL | VL | VL | VL | VL | VL |
| Thermal factor | L | VL | VL | VL | VL | VL | L | VL | VL | VL | VL | VL |
| Decomm. costs | VL | VL | VL | VL | VL | VL | VL | VL | VL | VL | VL | VL |
| Backfill costs | VL | VL | VL | VL | VL | VL | VL | VL | VL | VL | VL | VL |

[a]Sensitivity: VH-very high (changes in storage plus disposal costs ≥ 15%); H-high (6% ≤ changes ≤ 15%); M-moderate (1% ≤ changes ≤ 3%); L-low (1% ≤ changes ≤ 3%); VL-very low (changes ≤ 1%).

greater for a FHLW cycle, since the period of operations is longer than in the other cycles. The storage capital cost, which includes the costs of the storage casks is very important because of two reasons; first, the cost is incurred very early and is not very discounted; second, if the capital cost of storage decreases, a larger cost reduction may be achieved by delaying disposal. If delay of disposal is not permitted, the sensitivity to the storage capital costs is reduced. The delay of backfilling, from the reference of 5 years to a possible maximum of 25 years, also has a great impact on disposal costs, except in the FHLW cycle, where backfilling volumes are at a minimum and half of the backfilling operations are always 30 years delayed. By imposing a delay of room backfilling of 25 years, an additional cost between 12 and 14% of storage plus disposal costs may be incurred in a SF/HLW cycle and about 4 % in a FHLW cycle. The reason for this large penalty is that the facility must be kept in operation for a longer time if backfilling is delayed.

The model shows a moderate sensitivity to variations in operating costs of the facilities, and since the repository design was intended to minimize the room dimensions, the sensitivity to underground operations is generally low. The sensitivity to variations in the thermal loading is generally very low, except in the more restricted cases, such as SF disposal in basalt and salt, where it is above 1 % (low). In general the response of the model is greater for variations in parameters that affect a larger fraction of the total costs, and for changes in costs that are incurred early in the operational life of the

MRS-repository system.

## C. Recommendations for Future Work

The parameters that have shown a large impact in the outcome of the economic model should be further investigated, for they can result in considerable cost differences. Transportation of SF and some design changes in the repository were analyzed separately in the present study with the purpose of determining the possible impact that they could produce in the waste isolation costs. These items are enumerated below:

- The alternative of purchasing the transportation casks instead of leasing them from the manufacturer, could lead to savings in the entire transportation (reactors to MRS and MRS to disposal site) of over $1,000 M (1987 dollars), depending on the location of the repository. For the case of an MRS located in Tennessee, the DOE transportation costs could be reduced by an amount ranging from $200 M to $500 M.
- The current design for the disposal packages includes a thick carbon steel reinforcement and a Ti overpack, the first for structural integrity and the second for corrosion resistance. The issue of structural integrity should be further investigated, in order to determine whether a thin canister full of consolidated fuel rods or HLW glass would collapse under the expected lithostatic or hydrostatic pressure in the repository; the acceptability of the increased risk of leakage

in case of structural failure should also be determined. If the Ti-carbon steel reinforcement could be replaced by a Ti canister, for instance, the disposal costs could be reduced by an amount ranging from \$70 M to \$350 M, depending on the host rock and the canister dimensions.

- The estimated borehole drilling costs are rather high, especially in granite and basalt, where fine drilling and blasting techniques are assumed to be used. If an alternative borehole drilling method were developed to reduce the drilling costs, a significant cost reduction could be achieved. Assuming that a new method could be developed with a cost reduction by a factor of 3 in borehole drilling costs, the savings in disposal operations would range between \$50 M and \$150 M, again depending on host rock and back end cycle.
- In reference repository designs, 2 waste shafts are assumed to be constructed for disposal of HLW. Given that the number of canisters disposed per day is not very large, the possibility of using the main waste shaft for transferring LLW as well should be studied. Elimination of the LLW shaft would result in savings of \$11 M to \$35 M. Also, the possibility of eliminating more shafts (using for example the waste shaft as one of the ventilation shafts) would further reduce the costs. Furthermore, eliminating shafts improves the safety of the repository as a waste isolation system, since fewer intrusions and disturbances are created in the geologic formation.

- The SF hardware and cladding hulls waste forms have relatively low radioactivity levels and heat generation rates, so that they could be simply emplaced on the floor of the disposal rooms instead of being emplaced in expensive boreholes. Estimated cost reductions by this alternative emplacement method would be between \$35 M and \$55 M for a once-through cycle, and between \$85 M and \$130 M for a reprocessing cycle.
- The need for a 25-year period of retrievability should also be the subject of deeper investigation. This constraint, which would imply a delay of backfilling of 25 years would increase the disposal costs for SF/HLW by more than \$400 M, and about \$150 M for FHLW disposal.

All these items mentioned above have an impact on waste disposal costs large enough as to make worthwhile the expenses in research and development that would be required. Several of the possible alternatives mentioned point directly to performing a thorough comparative risk analysis of the back end of the nuclear fuel cycle. The feasibility of the alternative overpack design, or the retrievability period, for example, can only be answered from a risk analysis standpoint. Related also to the risk analysis is the possibility of imposing a maximum temperature limit for the waste form in the long range. If this additional constraint was found to be necessary, the maximum permissible thermal loadings would be lowered, much more for SF than for other waste forms, with the corresponding impact on disposal costs. Furthermore, a comparative risk analysis between the 5 repository locations and the 3 back end cycles should complement the economic analysis in order to decide which is the best waste storage and disposal solution.

Finally, the design of the facilities should be studied in order to minimize the cost impact, in particular, that of the capital cost of the storage facility and the storage casks. If the cost of the storage casks can be decreased by employing a different design, the possibility of delaying disposal would become an economic incentive, and the disposal cost could be lowered. This last item, however, presents more uncertainty, since there are political pressures to start disposal as soon as possible, and a further delay of the repository might not be acceptable.

The range of costs obtained in the present work compare reasonably well with existing estimates (69,74,75,86) if a zero discount rate is used and the contingency values are subtracted from the literature values. The values estimated here are usually in the lower end of the range of costs in the literature, which is consistent with the approach of optimizing the thermal loadings and minimizing the excavation requirements. Nevertheless, the utilities fear that the cost of the DOE program as specified in the NWPA will rise above $23 Billion (1985 dollars) (128) and that the disposal costs will be higher than what has been estimated up-to-date. If, in fact, the disposal costs were to be much higher than the estimates predict, the different research projects that have been proposed above, and possibly others such as development of remote emplacement equipment, would become even more significant, and they could presumably lead to bigger cost reductions than those that have been calculated in this project.

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# IX. ACKNOWLEDGEMENTS

I wish to express my deepest gratitude to my major professor, Dr. Bernard I. Spinrad, not only for his constant advice, help, and guidance during the performance of this research, but also for his kindness, friendship, and encouragement during my stay at Iowa State.

I also want to thank Drs. A.F. Rohach, D.M. Martin, L.E. Burkhart, and M.M. Razzaque for their help as committee members.

I am indebted to the Department of Nuclear Engineering and to the Engineering Research Institute for providing financial support.

I want to extend my appreciation to my fellow graduate students; in particular John Sankoorikal, Mike Winter, Okan Zabunoglu, Uner Colak, Niyazi Sokmen, and Scott State for their good advice and many hours of discussion, and Ramin Mikaili for his suggestions and his radio, which kept me awake during long nights at the Nuc E Lab.

Very special thanks are due to my parents Toni and Nita and my sisters Anna and Nuri, who have always been with me regardless of the distance; and my special friend Anna, who has made the time spent in this work more meaningful.

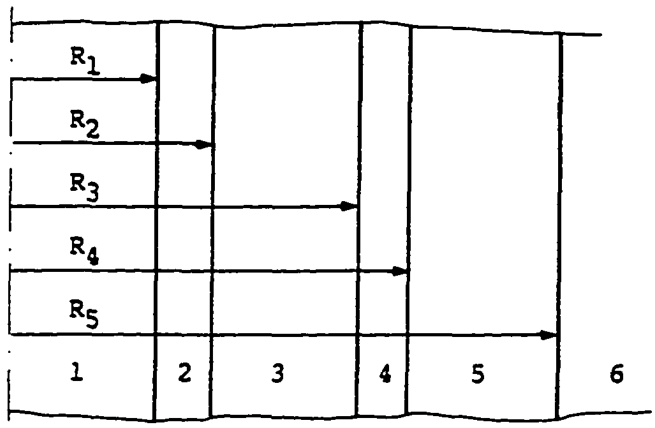
# X. APPENDIX A. VERY-NEAR-FIELD AND FAR-FIELD THERMAL MODELS

## A. Very-Near-Field Thermal Analysis Model

The VNF model is concerned with the heat transfer and temperature distribution in the region comprising the canister and emplacement borehole. The purpose of the VNF model is to determine possible maximum heat loadings in the canister and the maximum permissible temperatures in the rock, to ensure that the Very-Near-Field temperature constraints are not violated. The VNF thermal model was applied to the borehole designs described in Chapter IV, which include SF and HLW waste forms, 3 canister sizes for SF, 3 canister sizes with 3 different waste concentration for HLW, and the effect of an air gap surrounding the canister in each of the previous cases. In each situation the temperature distribution in the canister and borehole was determined for different ages of the waste, ranging from 10 to 100 years after removal from the reactor.

Heat transfer in the vertical direction was neglected and only the radial temperature distribution was estimated. When there is no air gap surrounding a HLW canister, heat transfer takes place by conduction alone and an analytical solution of the heat diffusion equation is possible. That is not the case for SF canisters, where heat transfer by convection and radiation occurs in the gas-filled spaces between consolidated rods. When an air gap is included in the borehole design, convection and radiation heat transfer through the gap must be accounted for and a semi-analytical model is used.

A borehole design in the general form is shown in Figure A.1, where the material, dimensions and temperature nomenclature is included. In solving the temperature equations, the volumetric heat source was considered uniform in the case of HLW glass, which is to assume that the glass has a uniform concentration of waste oxides. For SF, however, because of varying burnup along the height of the fuel rod, an adjustment had to be made. The volumetric heat source used was the average source multiplied by a 1.29 peak-to-average factor (129).




1 - Waste form  2 - Canister/Overpack  3 - Air Gap
4 - Sleeve  5 - Bentonite buffer  6 - Host rock

FIGURE A.1. A general borehole design

A temperature independent thermal conductivity for bentonite and HLW glass is assumed. A constant temperature drop through canister and sleeve was always considered, because of the high thermal conductivity of the metals used for these components. Because of the relatively small dimensions of the borehole, the times involved in reaching an equilibrium temperature distribution are short enough as to be able to consider a constant heat source in the canister. Hence, the temperature distributions are determined as steady state problems with different source strengths (corresponding to different source ages).

The expressions for the temperature drop (in °C) through the different components of the borehole are listed below:

$$T_1 - T_2 = \frac{Q' R_1^2}{4 k_g} \qquad (A.1)$$

$$T_2 - T_3 = 1 \qquad (A.2)$$

$$T_4 - T_5 = 1 \qquad (A.3)$$

$$T_5 - T_6 = \frac{Q' R_1^2}{2 k_b} \ln (R_5/R_4) \qquad (A.4)$$

where: $Q'$ = volumetric heat source, $w/m^3$

$k_g$ = HLW glass thermal conductivity, w/m-°C

$k_b$ = Bentonite buffer thermal conductivity, w/m-°C

As noted, equation A.1. is only valid for HLW, since for SF the dependence of the thermal conductivity on temperature cannot be neglected. The method used to estimate the temperature drop across the SF canisters is described in Section 1. Without the air gap included in the design, $T_3$ is equal to $T_4$. If an air gap around the canister is included then the temperature drop must be calculated. Heat transfer through the air gap includes conduction, convection and radiation, the importance of each mechanism depending upon the gap size and the temperatures involved. To calculate this temperature drop through the gap, an iterative process was used, as described in Section 2.

1. Temperature drop in spent fuel canisters

A canister of SF contains a bundle of consolidated fuel rods, normally forming a triangular pitch. Each rod is in contact with neighboring rods and a gas-filled space exists between each set of three rods. Heat is transferred by conduction from rod to rod and by convection and radiation through the gas filled spaces. A detailed heat transfer analysis becomes very complicated, and for practical purposes an overall heat transfer coefficient must be estimated in the form of an effective thermal conductivity. This lumped thermal conductivity is strongly temperature-dependent because of the radiative part of the heat transfer. Given the nature of the heat transfer mechanisms, it has been suggested (54) that the effective conductivity must be proportional to $T^3$, where the proportionality constant depends upon the number of rods in the canister, their diameter, and that of the canister.

Based on the proposed behavior of k with temperature and correlation coefficients for the constant of proportionality, a plot of the effective thermal conductivity of SF as a function of temperature has been published (54,107), as well as a set of curves to estimate the temperature drop across the canister using the heat output as a parameter (54). However, these estimates do not include the effect of radial reinforcement spines inside the canister. More recent studies

(55,86) which account for the contribution of the reinforcements to the total heat transfer, report much smaller temperature drops than those which did not include the fins.

To obtain an expression for the temperature across the SF canister the heat conduction equation was solved for a temperature dependent thermal conductivity:

$$\frac{d}{dr} \left( k_f \, r \, \frac{dT}{dr} \right) = -Q' \qquad (A.5)$$

where r is the radial dimension and $k_f$ is the effective thermal conductivity given as:

$$k_f = A + C \, T^3 \qquad (A.6)$$

Solving equation (A.5),

$$4 \, A \, (T_1 - T_2) + C \, (T_1^4 - T_2^4) = Q' \, R_1^2 \qquad (A.7)$$

By using power and temperature data from published plots (54), the constants A and C in equation A.7 were found with a least-squares method. The expression for the effective conductivity is:

$$k_f = 0.1448 + 6.96E\text{-}9 \; T^3 \qquad (A.8)$$

The estimated thermal conductivity agrees well with the published curve (54,107), as can be seen in Figure A.2. Notice that the best agreement is in the middle of the range, which covers the temperatures of interest here.

The effective conductivity found must still be corrected for the inclusion of radial fins in the canister. Unfortunately, only two data

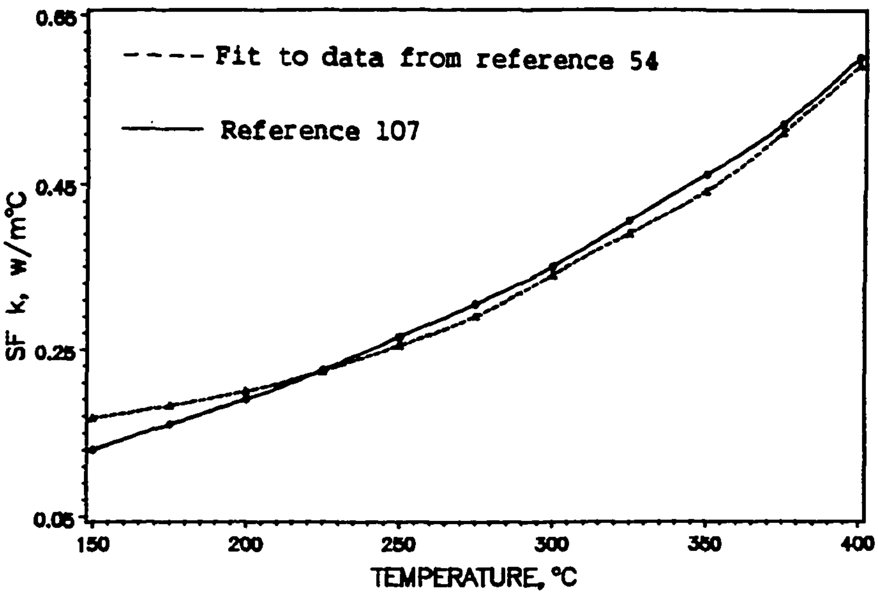



FIGURE A.2. Effective thermal conductivity of spent fuel

point estimates are available, corresponding to two different canister heat outputs, 3300 and 6600 w. Temperature drops obtained with computer simulations for these two cases (55,86) have been used to correct the thermal conductivity of equation A.8. A conductivity increased by a factor of 4.4 was found to be appropriate to predict the reported temperature drops in the two cases. The final expression for the conductivity used in this project is:

$$k_f = 0.6371 + 3.0628E\text{-}8\ T^3 \qquad (A.9)$$

and the expression for the temperature drop across the SF canister:

$$2.55\ (T_1 - T_2) + 3.06E\text{-}8\ (T_1^4 - T_2^4) = Q'\ R_1^2 \qquad (A.10)$$

With $T_3$ fixed at the maximum permissible value, $T_4$ is found after an iterative process, or vice versa, depending on whether the limiting factor is the canister centerline temperature or the bentonite temperature. It is necessary to mention that because of the importance of the effective thermal conductivity of the spent fuel, experimental data should be sought rather than relying on computer simulations. An experiment might not be expensive, especially when compared with the expenses that could result from miscalculating the value of the thermal conductivity.

2. Air gap calculations

The temperature drop across the gap depends on the thickness of the gap, which is another variable that must be investigated. The effect of the air gap size on the temperature drop has been studied (130) and it has been reported that a gas-filled gap presents better heat transfer characteristics than the same gap filled with crushed rock or other low conductivity materials. A combination of conductive, convective and radiative heat transfer occurs through the air gap. Radiation does not depend strongly on the size, but rather on the temperature of the surfaces. At small thicknesses (less than or equal to 1 cm) conduction is important and little convective heat transfer takes place. For larger thicknesses, convection dominates conduction. In this analysis the inside surface of the gap has been taken as the heat transfer surface, a justifiable approximation given the relative small gap sizes involved.

The radiative heat transfer can be calculated analytically as a function of the surface temperatures:

$$Q_r = \frac{\sigma A_i \,(T_3^4 - T_4^4)}{\dfrac{1}{\epsilon_i} + \dfrac{1}{F} + \dfrac{(1-\epsilon_o)\,A_i}{\epsilon_o\, A_o}} \tag{A.11}$$

where: $Q_r$ = radiative heat transfer, w

$\sigma$ = Stephan-Boltzman constant

$A_i$ = gap inside surface area, $m^2$

$A_o$ = gap outside surface area, $m^2$

$\epsilon_i$ = emissivity of inside gap surface

$\epsilon_o$ = emissivity of outside gap surface

F = view factor from inside to outside surface

The emissivities of the two metal surfaces have been assumed to be equal to 0.6, which corresponds to an average value for heated steel (131).

Determination of the convective heat transfer requires the use of semi-empirical expressions to estimate the heat transfer coefficient. In this particular case, expressions for natural convection through an enclosed vertical gas layer are to be used. There are correlations to determine the Nusselt number for this problem. In previous studies (106,130) of air gaps around a waste canister different approximations were used, one of which is valid for fluids covering a range of Prandtl numbers (132) and another specifically obtained for convection in gas layers (133). The latter set of correlations is used in the present model:

$$Nu = 0.18\ (Gr)^{1/4}\ (L/S)^{-1/9} \qquad 20000 \le Gr \le 200000 \qquad (A.12)$$

$$Nu = 0.065\ (Gr)^{1/3}\ (L/S)^{-1/9} \qquad 200000 \le Gr \le 1\ 10^7 \qquad (A.13)$$

where: Nu - modified Nusselt number

Gr - Grashof number = $\beta\ g\ S^3\ \Delta T\ /\ \nu^2$

$\beta$ - coefficient of gas thermal expansion, 1/°K

g - gravitational acceleration, $m^2/s$

S - gap thickness, m

$\Delta T$ - temperature drop through gap, °K

$\nu$ - air kinematic viscosity, $m^2/s$

L - height of the air layer, m

The modified Nu number, with characteristic length equal to the gap thickness, is used to estimate the equivalent heat transfer coefficient, accounting for conduction and convection:

$$h = Nu\ k_a/S \qquad (A.14a)$$

where $k_a$ is the thermal conductivity of air.

In equations A.12 to A.14 the properties of air are evaluated at the mean temperature of the gap. When the gap size is very small, conduction dominates over convection and the heat transfer coefficient is expressed as:

$$h = k_a/S \qquad (A.14b)$$

Once the conductive-convective heat transfer coefficient is estimated the heat transferred by these mechanisms is calculated by setting temperature $T_3$ and assuming $T_4$ in equation A.15.

$$Q_c = h\,A_i\,(T_3 - T_4) \qquad \text{(A.15)}$$

An iterative process is then performed in which $T_4$ is changed in equations A.11 to A.15 until the sum of the radiative and conductive-convective heat transferred equals the total heat output of the waste canister.

The effect of the gap size was first studied for three different canister diameters and heat outputs ranging from 3000 to 8000 w. The temperature drop through the gap and the equivalent thermal conductivity of the gap were calculated for thicknesses from 1 to 20 cm. The qualitative results were very similar, regardless of the canister size and loading. The typical behavior found for the temperature drop through the gap as a function of the gap thickness is shown in Figure A.3 and the comparison of the equivalent thermal conductivity of the gap with that of the bentonite buffer is shown in Figure A.4.

For gap thicknesses over 5 cm, air filling results in better heat transfer than bentonite buffer filling. A gap thickness of 1 cm or less would result in the smaller temperature drops, as seen in Figure A.3. However, a 2 cm clearance in diameter would certainly increase the difficulty of remotely controlled emplacement operations for a 4 meter-long (SF) canister. It can also be seen that the temperature drop across the gap decreases slowly by increasing the gap size beyond the 5 cm mark. What is gained by slightly reducing the temperature

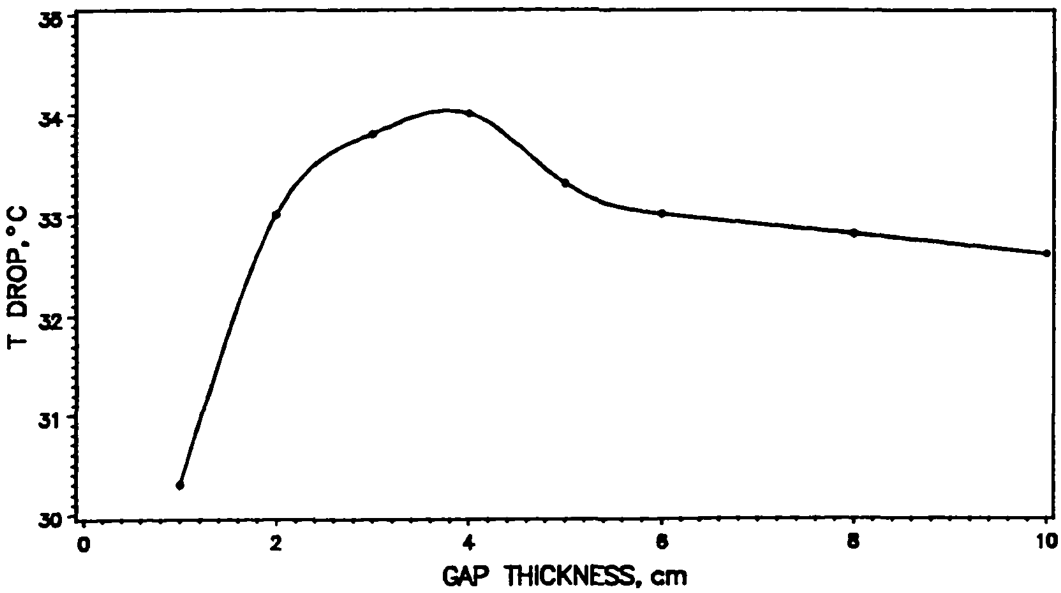



FIGURE A.3. Temperature drop across the gap vs. gap thickness

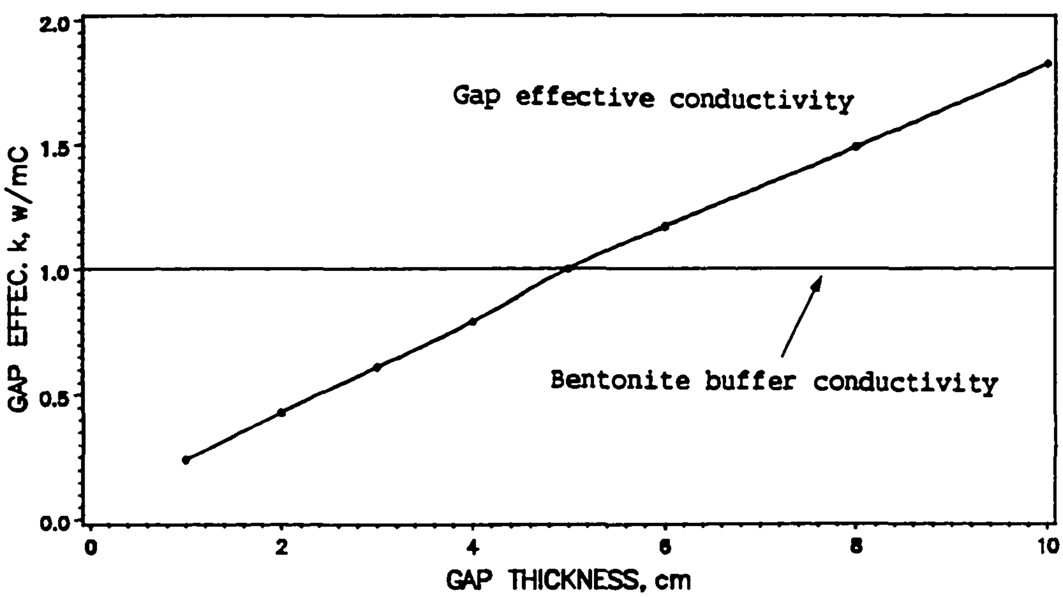



FIGURE A.4. Equivalent gap conductivity vs. gap thickness drop might not compensate for the increase in borehole drilling expenses.[5] Thus a gap size of 6 cm has been selected, corresponding to the region immediately beyond the maximum T. This provides a 12 cm clearance in diameter that should ease the emplacement operations. Given the similarity of results obtained for 3 different canister sizes and 3 different canister heat loads, a unique gap thickness of 6 cm is used in all borehole designs studied.

## B. Far-Field Thermal Analysis Model

The maximum surface uplift criterion was used to determine the allowable FF thermal loadings. A simple one-dimensional semi-analytical model proposed by Malbrain and Lester (104) has been used in the present study. The repository is considered a plane source, infinite in the horizontal directions. The heat conduction equation is solved for a semi-infinite region in the vertical direction with constant rock properties. The solution for the temperature increase in the rock as a function of the depth is given by (134):

$$\Delta T(z,t,A) = \frac{1}{\sqrt{4\pi\delta}} \int_0^t q(t+A-\tau)\ \frac{1}{\sqrt{\tau}}\ \{EXP(-(z-H)^2/4\delta\tau) - EXP(-(z+H)^2/4\delta\tau)\}\ d\tau \tag{A.16}$$

where: z = depth below surface, m

H = repository depth, m

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[5] It must be noted that the range of temperature drops is small.

$t$ = time after emplacement, years

$A$ = waste age at emplacement, years

$\delta$ = rock thermal diffusivity, $m^2$/year

$q$ = source strength, m °C/year

The heat source strength can be expressed as a product of other variables:

$$q = FFM \cdot Q / \rho \cdot Cp,$$

where FFM is the Far-Field mass loading, MTHM/$m^2$, and Q is the heat generation rate, w/MTHM.

Considering the rock as a thermoelastic medium restrained in all directions except at the surface, the displacement in the vertical direction is given by:

$$u(z,t,A) = -\frac{1}{2}\,\alpha \left(\frac{1+\nu}{1-\nu}\right) \int_z^{\infty} \Delta T(z',t,A) \quad dz' \qquad (A.17)$$

where u is the displacement in m.

Rock salt has a thermal expansion coefficient about 6 times larger than most of other rocks. If the surface uplift is calculated for a repository in salt under the consideration that the only existing rock is salt, the resulting allowable FF loading will be very conservative. In reality, the maximum surface uplift would not be as large, since there are other rocks, with smaller $\alpha$, above and below the salt layers. The model has therefore been modified to accomodate the possibility of different rock properties along the z direction. Stratigraphic data from the proposed salt repository in Deaf Smith Co., Palo Duro, Texas, has been used to determine the thickness of the salt formation (95). The salt formation at that location extends from approximately 550 m to 975 m. Although several rock compositions exist above and below the salt formation their properties have been averaged, using data for the proposed repository location. Three regions have been considered:

- from the surface to 550 m, with average $\alpha$=14 $10^{-6}$ $°C^{-1}$
- from 550 to 975 m, the salt formation.
- from 975 m to $\infty$, with average $\alpha$=16.2 $10^{-6}$ $°C^{-1}$

In granite, tuff and basalt repositories, the distinction of three different regions has not been necessary, since the rock strata surrounding these formations present similar thermal expansion coefficients. To calculate the total surface uplift, as a function of time, equation A.17 is integrated from 0 to $\infty$, resulting in the following expressions:

$$u(0,t,A)=\frac{FFM}{2}\int_0^t Q(t+A-\tau)\left\{K_1\left[\mathrm{erf}[\frac{975-H}{\sqrt{4\delta_1\tau}}]-\mathrm{erf}[\frac{975+H}{\sqrt{4\delta_1\tau}}]\right]\right.$$

$$+K_2\left[\mathrm{erf}[\frac{975+H}{\sqrt{4\delta_2\tau}}]-\mathrm{erf}[\frac{975-H}{\sqrt{4\delta_2\tau}}]+\mathrm{erf}[\frac{550-H}{\sqrt{4\delta_2\tau}}]-\mathrm{erf}[\frac{550+H}{\sqrt{4\delta_2\tau}}]\right]$$

$$\left.+K_3\left[\mathrm{erf}[\frac{550+H}{\sqrt{4\delta_3\tau}}]-\mathrm{erf}[\frac{550-H}{\sqrt{4\delta_3\tau}}]-2\mathrm{erf}[\frac{H}{\sqrt{4\delta_3\tau}}]\right]\right\}d\tau \qquad \text{(A.18a)}$$

where $K_i = \frac{\alpha_i}{\rho_i Cp_i}\ \frac{1+\nu_i}{1-\nu_i}$ , erf is the error function,

and the subindex denotes the region: region 1, below the salt formation, region 2 is the salt formation and region 3 is above the salt. For the other geologic formations, granite, tuff, and basalt, where uniform properties are considered, the 3 regions become 1 and equation A.18a simplifies to:

$$u(0,t,A)=FFM \frac{\alpha}{\rho Cp} \left(\frac{1+\nu}{1-\nu}\right) \int_0^t Q(t+A-\tau) \quad erf[\frac{H}{\sqrt{4\delta\tau}}] \, d\tau \qquad (A.18b)$$

With a fixed maximum surface uplift of 1.5 m equations A.17 or A.18a are solved for FFM, the maximum permissible far-field mass loading. The integral is solved numerically for different integration times, t, since the surface uplift is a function of time. In solving the integral the error function is approximated by the following expansion (135):

$$erf\ x = 1 -(ay + by^2 + cy^3)EXP(-x^2) \qquad (A.19)$$

where $y = (1+dx)^{-1}$ and

$a = 0.348 \qquad b=-0.096 \qquad c=0.748 \qquad d=0.47$

In the calculations in salt, if salt properties had been considered for the entire depth, the FF allowable loading would have been lower, by as much as 50 %. Still, with the 3-region approach, salt has the lowest FF loadings among the four rocks. The FF is still restrictive with the three-region model because the salt region is thick and corresponds to the zone with the largest temperature rise, resulting in a large thermal expansion.

# XI. APPENDIX B. NEAR-FIELD THERMAL MODEL

## A. Development of the Model

To predict the temperature rise at a given location in the Near-Field region a semi-analytical model in 3 dimensions has been developed. Although complex multi-purpose numerical models have been applied to the thermal analysis of a nuclear waste repository (136,137), they result in expensive computer runs which make them inappropriate for a generic parametric analysis. Simplified models have also been developed, such as the FLLSSM (138, 139) (Finite Length Line Source Superposition Model). The FLLSSM assumes that all canisters in the repository are line sources and evaluates the contribution of each source to the temperature increase in the desired location. This computation requires accounting for the superposition of tens of thousands of sources and is still quite time-consuming and costly.

A further simplification, still based on the superposition concept, has been applied by Malbrain and Lester (104); it consists of homogenizing most of the sources in the repository to slab sources. The relative accuracy of such an approximation has also been discussed, and the only significant source of error turns out to be the assumption of temperature-independent properties in the rock medium. A variation of the slab homogenization superposition model is presented in this section for its application to the temperature calculations in the Near-Field.

The repository medium is treated as an infinite homogeneous medium, whose thermal properties are independent of temperature. A canister in the center of the repository is chosen as the origin of coordinates. This canister is considered a line source of length equal to the active height. A number of canisters along the same room are also treated as line sources. Other canisters in the same room but far from the origin and canisters emplaced in other rooms are homogenized into slab sources, whose thickness equals the active canister height, as well. A representation of this geometry can be seen in Figure B.1. There are in total 2N+1 canisters that are treated as line sources, this N chosen such that an increase in N by 1 does not produce a significant change in the temperature calculated. Slab sources A and B, as seen in Figure B.1, are semi-infinite in the x and y directions. Slab sources C and D are semi-infinite in the x direction and have a width equal to the room-to-room distance[6] (room plus pillar width). The room is not taken as an empty space, but rather it is assumed that is filled with material having the same properties as the host rock.

The temperature rise at any location in the Near-Field region is obtained by adding up the partial temperature increases produced by the different sources considered, i.e., the central line source, the 2N line sources in the x direction, and the 4 semi-infinite slab sources. The calculation of the contribution of each of these sources is presented below.

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[6] Alternative definitions of the slabs do not change the results.

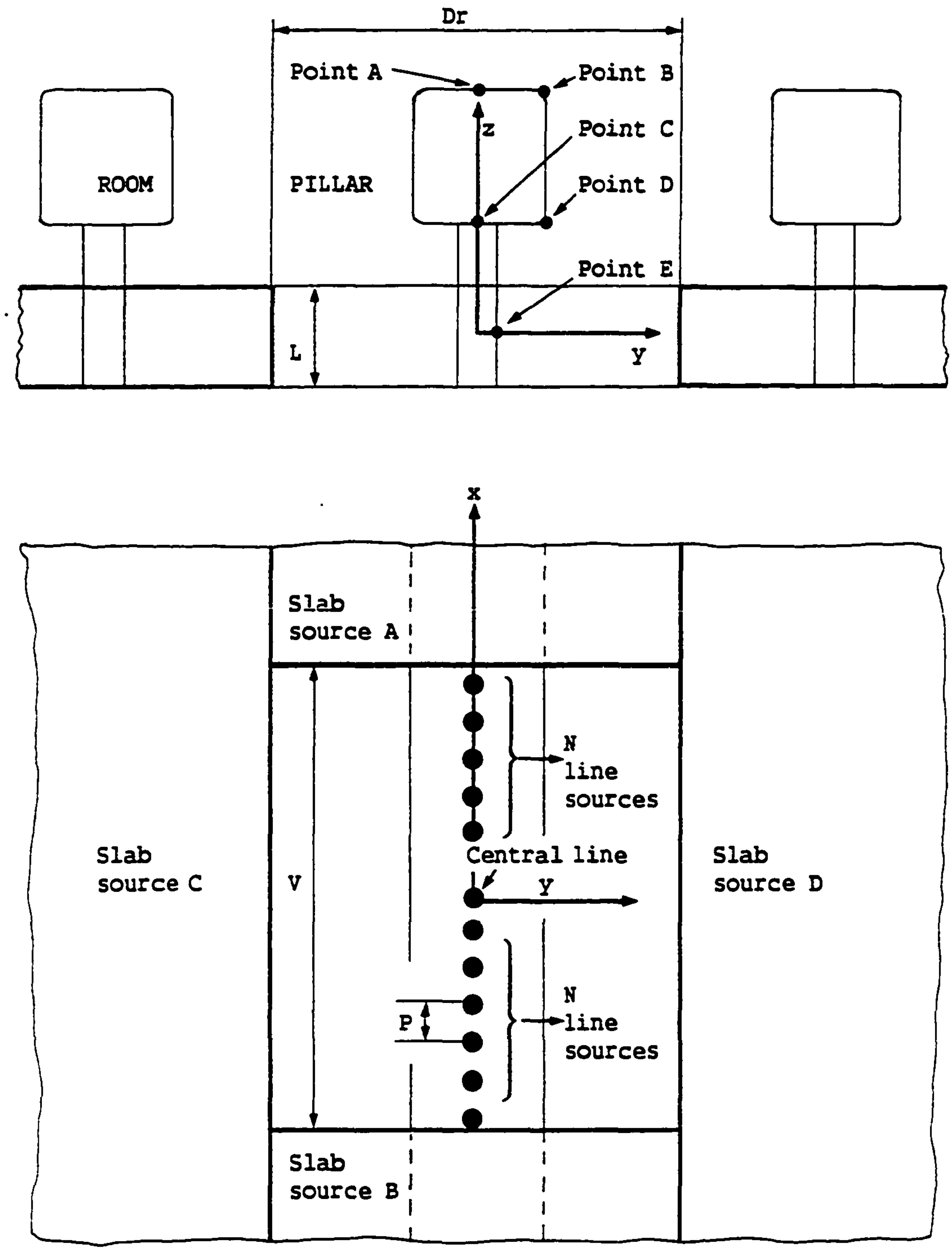



FIGURE B.1. Heat source layout for the NF model

Under the assumptions of the model only conductive heat transfer takes place and the temperature increase is found by solving the heat diffusion equation:

$$\nabla^2 T = \frac{1}{\delta}\frac{\partial T}{\partial t} \tag{B.1}$$

The general solution for the temperature increase at a point r of coordinates (x,y,z) due to an instantaneous point source at $x'$, $y'$, $z'$, in an infinite medium, can be expressed (134)

$$\Delta T(r) = \frac{q'}{8(\pi\delta t)^{3/2}} e^{-\left[\frac{(x-x')^2+(y-y')^2+(z-z')^2}{4\delta t}\right]} \tag{B.2}$$

where $q'$ is the source strength, in units of °C $m^2$.

Integration of equation B.2 with respect to $z'$ from $-L/2$ to $+L/2$, will result in the temperature rise at r due to a source of length L located at $x'$, $y'$, equation B.3.

$$\Delta T(r) = \frac{q''}{8\pi\delta t}\left[\operatorname{erf}\left[\frac{z+L/2}{\sqrt{4\delta t}}\right]-\operatorname{erf}\left[\frac{z-L/2}{\sqrt{4\delta t}}\right]\right] e^{-\left[\frac{(x-x')^2+(y-y')^2}{4\delta t}\right]} \tag{B.3}$$

where $q''$ is expressed in units of °C $m^3$.

Equation B.3 is the starting point for determining the temperature increase at point r due to any of the sources considered in the model. The difference from one source to another resides in the integrations performed in the $x'$ and $y'$ directions to account for the source location.

1. Temperature increase due to the central line source

The central line source is located at the origin of coordinates. Since equation B.3 was developed for an instantaneous source and the radioactive waste is a continuous (although decaying) heat source, the equation is integrated with respect to a variable $t'$ (time) from 0 to a time t, with $x'$ and $y'$ set to 0. The result will be the expression for the temperature rise at r at time t. A change of variables has been made in the integral, and the difference $t-t'$ has been renamed as $\tau$. The source strength, which would now be given in units of °C $m^2$ / year has also been changed into more familiar terms:
source strength = Mc · Q(t) / $\rho$ Cp , where Mc is the canister mass loading (MTHM) and Q is the heat generation rate as a function of time after emplacement and age of the waste at disposal, in w/MTHM.

With these notation changes included, the temperature increase at r at time t due to the central source is given by the following equation:

$$\Delta T_a(r,t) = K\int_0^t \frac{Q(t+A-\tau)}{\tau}\left[\mathrm{erf}\left[\frac{z+L/2}{\sqrt{4\delta\tau}}\right]-\mathrm{erf}\left[\frac{z-L/2}{\sqrt{4\delta\tau}}\right]\right]e^{-\left[\frac{x^2+y^2}{4\delta\tau}\right]}\,d\tau \tag{B.4}$$

where $K = Mc\ (8\ \pi\ \delta\ L\ \rho\ Cp)^{-1}$.

2. Temperature increase due to other line sources

A similar procedure to that used for the central source is followed here. Equation B.3 is integrated with respect to time for each of the N sources in the positive-x direction and each of the N sources in the negative-x direction. The coordinates of the line sources are, respectively:

$y' = 0 \quad x' = iP \quad i = 1 \text{ to } N$

$y' = 0 \quad x' = -iP \quad i = 1 \text{ to } N$

where P is the canister pitch.

No integration with respect to $x'$ and $y'$ is necessary for these sources either; only the time integration. The contribution of all 2N sources to the temperature rise at $r$ at time t is lumped in a single expression, B.5:

$$\Delta T_a(r,t) = K \sum_{i=1}^{N} \int_0^t \frac{Q(t+A-\tau)}{\tau} \left[ \text{erf}\left[\frac{z+L/2}{\sqrt{4\delta\tau}}\right] - \text{erf}\left[\frac{z-L/2}{\sqrt{\delta\tau 4}}\right] \right] e^{-\frac{y^2}{4\delta\tau}}$$

$$\cdot \left[ e^{-\frac{(x-iP)^2}{4\delta\tau}} + e^{-\frac{(x+iP)^2}{4\delta\tau}} \right] d\tau \qquad \text{(B.5)}$$

3. Temperature increase due to slab sources

The integration performed with respect to $z'$ still holds, since the thickness of the slabs is also L. But now the sources extend over the x and y domain as well, and $x'$ and $y'$ must be integrated over their ranges. The ranges of integration for the four slabs are as follows (see Figure B.1):

Slab A $\quad y'$ from Dr/2 to $\infty$

$x'$ from $-\infty$ to $\infty$

Slab B $\quad y'$ from $-\infty$ to $-Dr/2$

$\qquad\quad x'$ from $-\infty$ to $\infty$

Slab C $\quad y'$ from $-Dr/2$ to $Dr/2$

$\qquad\quad x'$ from $V/2$ to $\infty$

Slab D $\quad y'$ from $-Dr/2$ to $Dr/2$

$\qquad\quad x'$ from $-\infty$ to $-V/2$

All integrations in the four slabs result in differences of the error function of different arguments. Lumping the results from the four different slabs, some of the terms cancel out, and the expression becomes a little simpler for the time integration, which is performed as before, and with the same notation changes. The final result for the temperature increase at a point r at a time t due to the four slab sources is given in equation B.6:

$$\Delta T_C(r,t) = \frac{Mc}{8LPDr\rho Cp}\int_0^t Q(t+a-\tau)\left[\mathrm{erf}\left[\frac{z+L/2}{\sqrt{4\delta\tau}}\right]-\mathrm{erf}\left[\frac{z-L/2}{\sqrt{4\delta\tau}}\right]\right]$$

$$\cdot\left\{4+\left[\mathrm{erf}\left[\frac{y+Dr/2}{\sqrt{4\delta\tau}}\right]-\mathrm{erf}\left[\frac{y-Dr/2}{\sqrt{4\delta\tau}}\right]\right]\left[\mathrm{erf}\left[\frac{x+V/2}{\sqrt{4\delta\tau}}\right]-\mathrm{erf}\left[\frac{x-V/2}{\sqrt{4\delta\tau}}\right]\right]\right\}d\tau \tag{B.6}$$

4. Total temperature increase

The final temperature rise at time t at point r is calculated by superposing the contributions of the different sources. By putting together the results obtained in equations B.4, B.5, and B.6 a single expression is used to summarize the temperature calculation model in the Near-Field region. The result is given in equation B.7.

$$\Delta T_t(r,t) = \frac{Mc}{8LDrP} \int_0^t Q(t+A-\tau) \left[ \mathrm{erf}\left[\frac{z+L/2}{\sqrt{4\delta\tau}}\right] - \mathrm{erf}\left[\frac{z-L/2}{\sqrt{4\delta\tau}}\right] \right]$$

$$\left\{ 4 - \left[ \mathrm{erf}\left[\frac{y+Dr/2}{\sqrt{4\delta\tau}}\right] - \mathrm{erf}\left[\frac{y-Dr/2}{\sqrt{4\delta\tau}}\right] \right] \cdot \left[ \mathrm{erf}\left[\frac{x+V/2}{\sqrt{4\delta\tau}}\right] - \mathrm{erf}\left[\frac{x-V/2}{\sqrt{4\delta\tau}}\right] \right] \right.$$

$$+ \frac{DrP}{\delta\pi\tau} e^{-\frac{(x^2+y^2)}{4\delta\tau}}$$

$$\left. + \frac{1}{8\pi\delta L\tau} \sum_{i=1}^{N} e^{-\frac{y^2}{4\delta\tau}} \left[ e^{-\frac{(x-iP)^2}{4\delta\tau}} + e^{-\frac{(x+iP)^2}{4\delta\tau}} \right] \right\} d\tau \tag{B.7}$$

The expression above is solved numerically and the temperature history is found in each case studied. The total temperature is found by adding the initial temperature of the rock medium to the result of the integral. The integrand of the above equation is ill-behaved, for there is a $\tau$ in the denominator of two of the terms, although the integrand does not go to infinity as t goes to zero. In the computer code used to solve the integral a cautious extrapolation quadrature method was employed, from the NAG routine library (140). An initial time of 1 $10^{-5}$ years was used to avoid the denominator zero in the computer. Decreasing the initial time by a factor of 10 showed no effect in the temperature increase estimate. Again, the expansion for the error function used was that listed in equation A.19.

## B. Near-Field Model Checks

The performance of the present model has been tested by comparing the results for some particular cases with those obtained with other existing models. One logical comparison is with the FLLSSM model, a superposition method that does not make use of the slab homogenization. The results predicted by the NF model should also be compared with those calculated with a detailed finite-element code, such as the HEATING5 computer code (137).

FLLSSM temperature calculations have been compared with those of HEATING5 (138) for a particular case of a repository in salt in which a density of disposal of 60 Kw/acre is achieved. The NF model developed in this appendix has been applied to the same specific case. The same thermal properties and room dimensions as used in the FLLSSM program have been used in the NF model, with one variation; in the FLLSSM code 2 rows of waste canisters per room are considered, whereas the NF model accounts for only 1 row. The canister mass loading has been doubled, so that the same density of disposal is obtained. This variation should only affect the calculation of the temperatures at locations very close to the waste canisters. Temperatures have been estimated at 5 different locations as defined by Kays et al. (138). The coordinates in the NF model of these five locations are:

| Point | x | y | z | (units in m) |
|---|---|---|---|---|
| A | 0 | 0.0 | 10.7 | |
| B | 0 | 2.7 | 10.7 | |
| C | 0 | 0.0 | 5.2 | |

| | | | |
|---|---|---|---|
| D | 0 | 2.7 | 5.2 |
| E | 0 | 0.5 | 0.0 |

The location of the five points is also indicated in Figure B.1. The results are listed in Table B.1, expressed in units of °F for consistency with the reference source.

From the numbers given in the table, the superposition models seem to overpredict the temperatures at short times after emplacement, an effect that is probably due to the lack of dependence of the thermal conductivity on temperature. Except for point E, very close to the canister, NF predicts lower temperatures than its superposition counterpart, as could be expected from doubling the canister mass loading. For the other points, NF gives a result that falls between those of H5 and FLLSSM at short times after emplacement. For longer times after emplacement, NF underestimates the temperature with respect to the other two models. In general the NF predictions are within reasonable ranges.

Another comparison is also presented, this time with a 3-dimensional Alternating Direction Implicit (ADI) numerical method, developed by Ferreri and Ventura (141). Results were compared for a particular case involving a generic repository in granite with canisters containing about 500 w at the time of disposal emplaced with a 5 m pitch in 1 row per room. The same conditions were fed into the NF model developed in this appendix, and the results obtained, in °C, are shown in Figure B.2. Temperature predictions for 3 different points are shown in that figure, corresponding to the coordinates (in

TABLE B.1. Comparison of the present model with FLLSSM and HEATING5 for a particular case

| Time after emplacement years | Temperature Point A[a] °F | | | Temperature Point B[a] °F | | | Temperature Point C[b] °F | | | Temperature Point D[b] °F | | | Temperature Point E[b] °F | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | H5[c] | FL[d] | NF[e] | H5 | FL | NF | H5 | FL | NF | H5 | FL | NF | H5 | FL | NF |
| 5 | 127 | 153 | 150 | 132 | 151 | 148 | 211 | 202 | 201 | 187 | 194 | 192 | 284 | 297 | 318 |
| 10 | 163 | 178 | 165 | 162 | 177 | 163 | 200 | 223 | 212 | 195 | 216 | 203 | 274 | 308 | 314 |
| 15 | 177 | 195 | 174 | 176 | 194 | 172 | 211 | 236 | 216 | 206 | 230 | 209 | 277 | 312 | 312 |
| 20 | 188 | 207 | 179 | 187 | 206 | 178 | 219 | 246 | 221 | 215 | 240 | 213 | 280 | 317 | 311 |
| 25 | 196 | 217 | 183 | 192 | 216 | 181 | 225 | 253 | 223 | 221 | 248 | 215 | 281 | 320 | 305 |
| 30 | 202 | 223 | 185 | 201 | 222 | 183 | 229 | 257 | 220 | 225 | 252 | 215 | 280 | 319 | 297 |

[a]Initial temperature = 83 °F.

[b]Initial temperature = 84 °F.

[c]HEATING5 code.

[d]Finite Length Line Source Superposition Model.

[e]Present Near-Field model with homogenized sources.

the NF model):

| Point | x | y | z | (units in m) |
|---|---|---|---|---|
| A | 0.0 | 0.0 | 1.2 | |
| B | 0.0 | 10.0 | 0.0 | |
| C | 2.5 | 0.0 | 0.0 | |

Again, the results obtained with the NF model seem acceptable, and they show the same behavior with respect to the predictions of HEATING5 as they did in the previous comparison. At short times after emplacement, the temperature estimated by NF is close to that estimated by HEATING5, and deviations appear at longer times after emplacement, when the NF model predicts lower temperatures. However, the ADI method shows a similar change in slope, occurring at similar times after disposal. This behavior is better seen in temperature predictions for locations B and C.

In summary, the NF model developed shows an acceptable accuracy for its use in a parametric analysis of a generic repository. The homogenization of part of the sources does not result in a big penalty, since the response of the NF model is not bad as compared with the FLLSSM response. The major source of error with respect to a finite element code such as HEATING5 appears to be the use in the NF model of an average thermal conductivity, which would account for the smaller slopes of temperature increase with time after emplacement seen in the NF results.

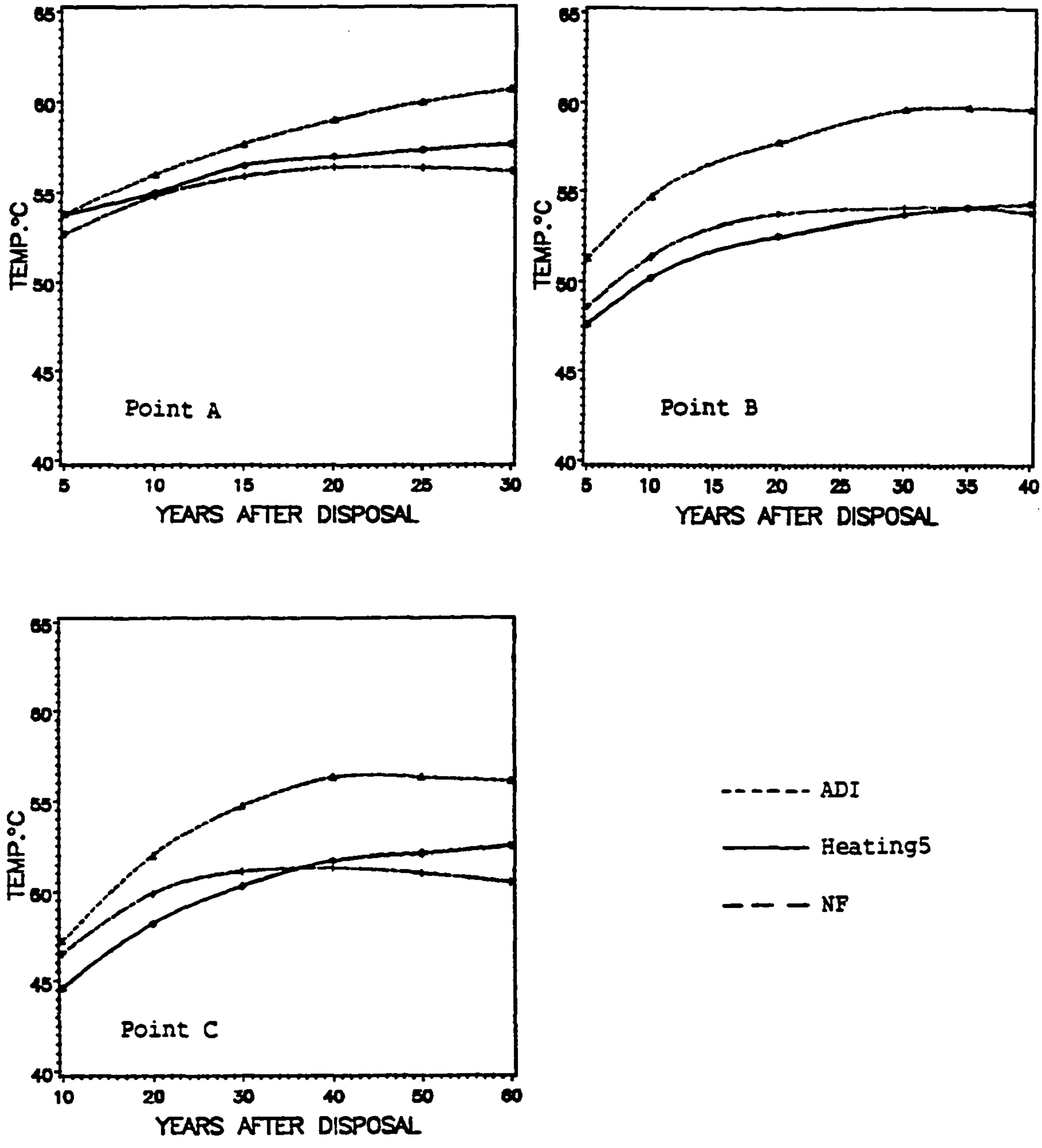



FIGURE B.2. Comparison of NF with and ADI method and HEATING5

# XII. APPENDIX C. BASIC COSTS

The unit costs for the different facilities and operations involved in the back end of the nuclear fuel cycle are presented in this Appendix. These costs were fed into the economic model. They were obtained from published costs estimates for the different operations and were modified to conform to the applicable scenarios analyzed in this study. The costs and their estimation procedure are explained in the following sections. All costs in this appendix are expressed in 1987 dollars. Published data for the GNP deflator were used to escalate the costs (142,143), and the factors used are shown in Table C.1.

TABLE C.1. Cost escalation factors from different years to 1987

| Years | Escalation factor |
|---|---|
| 1976-1987 | 1.8809 |
| 1977-1987 | 1.7879 |
| 1978-1987 | 1.6899 |
| 1979-1987 | 1.5735 |
| 1980-1987 | 1.4489 |
| 1981-1987 | 1.3268 |
| 1982-1987 | 1.2128 |
| 1983-1987 | 1.1442 |
| 1984-1987 | 1.1023 |
| 1985-1987 | 1.0612 |
| 1986-1987 | 1.027 |

## A. Transportation Costs

The cost of the transportation cask is estimated as a cask usage fee per day, since it is assumed that the transportation casks are leased from the manufacturer. Several references have used this approach (60,63,65,66) based on a DOE study (33). The cost estimate of the use charges is made on the assumption that the cask is used for 292 days a year, and includes amortization of the manufacturing cost, licensing, and maintenance and inspection after each shipment. Although the different references mentioned arrive at different cost estimates for the leasing fee, the procedure is always based on the method described in reference 33, so that the value estimated in the latter is used in the present study. The estimated cask leasing fee per day of usage is $4,990, in 1987 dollars.

The freight charges by rail have been estimated in reference 60 for different shipping distances. An approximation for calculating the shipping charges as a function of the distance is given in that reference. When the casks are loaded with spent fuel security measures must be taken, and the shipping expenses per unit weight are higher for a loaded cask than for an empty one. The correlations in both cases are:

$$\text{1987 dollars/1000 Kgs} = 4.10\ (d^{0.5860}) \quad \text{(loaded)}$$

$$\text{1987 dollars/1000 Kgs} = 3.76\ (d^{0.5895}) \quad \text{(empty)}$$

where d is the one-way distance. The weights of the reference IF-300 cask are 79,400 Kgs when empty, and 84,200 or 90,700 Kgs when loaded with unconsolidated or consolidated spent fuel respectively.

## B. MRS and Packaging Facilities Costs

Although the MRS and the packaging plant may be located at different sites, their costs estimates are discussed in the same section because of the linkage between some of the operations to be performed in them. When the MRS is not co-located there will be a waste receiving/handling building in both the MRS location and the disposal site. When the MRS is co-located with the repository, however, only one waste receiving facility is needed.

### 1. Facilities capital costs

Because of the similarities between some of the operations performed in the MRS and the packaging facility, we have tried to homogenize their costs. Published cost estimates cover a wide range of capacities and designs with notable differences in facilities capital costs, from an estimated capital cost of about \$250 M for a storage capacity of 72,000 MTHM (144) to a cost over \$450 M for a storage capacity of 7,000 MTHM (72).

More recent studies, based on the dry cask storage system show better agreement. A design which estimates the cost of the facilities by modules where the number of modules required depends on the receiving rate (75) would result in an estimate for the scenarios considered in the present study of about \$130 M for the receiving/handling installations, and \$69 M additional for a packaging line. Another PNL design (66) for an MRS facility reports cost estimates of \$137 M that would include off-site development, waste receiving/handling, service/utility facilities, and service systems. The same design including the Architect-Engineering expenses would result in a total cost of $150 M. Westinghouse (54,55) estimated the cost of a receiving and packaging facility based on an original design of a storage facility and modified to include the packaging line. The costs, which depend on the throughput of canisters per day (250 days/year of operation), are $108 M and $180 M for less than or more than 3 canisters per day respectively. An additional cost of $34 M is included if the facility is to consolidate the spent fuel.

The last three estimates presented are in reasonable agreement since the Westinghouse estimate accounts for the packaging module. The estimates to be used in the economic analysis model are based on the values presented. For the different scenarios, the capital costs estimated are as follows:

- MRS facility is not co-located with the repository, and includes the receiving/handling modules but no packaging facility. The capital cost estimate (66) is $150 M. Given the location of the MRS, the packaging facility in the repository must have another waste receiving/handling building, so that its cost is estimated (54,55) at:

  $108 M for throughputs $\leq$ 3 canisters[7] per day.

  $180 M for throughputs $\geq$ 3 canisters per day

  If consolidation takes place in the MRS facility, $34 M are

---

[7] These are SF (4.2 m long) canisters, and the cutoff point would be 9 if the canisters (1.3 m long) are for other waste forms.

added to the MRS facility capital cost; the $34 M are added to the capital cost of the packaging facility if consolidation is performed there.

- MRS facility is co-located with the repository, in which case only one receiving/handling module is required. To include all waste transfer operations in the same facility, it is assumed that the packaging line would be built in the MRS facility, so that its estimated cost would be (54,55) $180 M, and the packaging facility does not exist as such. This does not produce any conflict in operating cost estimates, since they are calculated separately for storage and packaging. Again the capital cost is increased by $34 M if consolidation is considered.

An additional capital cost item, which is always a part of the MRS facility is the cost of the storage transporter/crane, estimated at $2.7 M (66). Decommissioning costs are calculated for the facilities at the end of the operating period, with a reference value of 10 % of the capital cost.

2. Storage casks

This cost always applies to the MRS facility cost. The reference cask for the cost estimates is the REA-2023 metal cask, although casks from other manufacturers are likely to be used instead. However, given the design and capacity similarities, it is assumed that their cost would be similar to that of the REA-2023.

The cost of the metal cask REA-2023 is estimated (66,67) at $849,000. Because this is a very heavy and big cask, the transportation to the MRS will be different depending on the location of the facility. Charges for the transportation (65) to a location in the eastern half of the U.S. are about $14,000, whereas for an MRS in the West, the estimate is $44,600. Adding the transportation costs to the manufacturing costs, the total cost of the storage cask is:

| | |
|---|---|
| For MRS co-located with repository: | $893,600 |
| For MRS not co-located with repository: | $863,000 |

Each storage cask has an additional expense, corresponding to the storage field preparation and the installation of a concrete pad to support the cask. The two operations amount to $2,790 per cask (60,66).

3. Operating costs

The operation of the MRS and packaging facility depends upon the location of the MRS, and, for the operating costs of the packaging facility, there is a dependence on the waste form for disposal as well. To estimate the operating cost of the MRS facility, for consistency with the source of the capital cost, data from reference 66 have been used. However, the staffing estimated in the reference has been modified for adapting the cost to the applicable scenarios, for the original estimate also includes handling of TRU waste. The staff of 138 in waste handling plus 62 in support operations from the reference has been reduced to a total of 165, 120 in waste handling (in agreement with 57) and 45 for support. Support personnel includes a staff of 30 for security operations and about 10 % of the facility operating staff in administrative tasks. The average salary has been estimated at \$35,000 per year, for a total of \$5.2 M/year. Costs of utilities and maintenance have been calculated from data in reference 66 corrected by a factor equal to the ratio of the number of personnel and escalated to 1987 dollars, for a total of \$3.25 M/year. Thus, the total operating cost of the MRS is estimated at \$9.05 M per year, for a facility not co-located with the repository. When the MRS is co-located with the repository, a reduction in 50 % of the support personnel is assumed, as well as a 30 % reduction in maintenance/utilities. The operating cost in this case is \$7.24 M per year.

Westinghouse estimates (54,55) are used for the packaging facility operating cost. The cost given in the references is for SF canisters (4.2 m long) and includes receiving as well as packaging operations, and is given in the form of a fixed part and a package-dependent component. The receiving part is only necessary when SF is disposed and the MRS is not co-located. Based on the possibility of eliminating process lines or shifts for lower throughputs per day, the estimates are a function of the number of canisters overpacked per day:

| | | |
|---|---|---|
| PPD ≤ 1.5 | Cost = 6.06E6 + 14,500 PPY | 1987 \$/year |
| 1.5 ≤ PPD ≤ 3 | Cost = 8.24E6 + 11,200 PPY | 1987 \$/year |
| 3 ≤ PPD ≤ 4.5 | Cost = 9.60E6 + 11,000 PPY | 1987 \$/year |
| PPD ≥ 4.5 | Cost = 11.44E6 + 10,700 PPY | 1987 \$/year |

where PPD is the number of (4.2 m-long) packages per day, and PPY is total number of packages per year. Again, because the design is for long canisters, when the waste form to be overpacked is not SF, it is assumed that the cutoff points are 3 times larger, based on the dimensional equivalence of 3 canisters of HLW/FHLW and 1 canister of SF. These numbers do not include the cost of the overpacks.

When the MRS is co-located, no receiving operations are to be performed in the packaging facility, and the same is true when a reprocessing cycle is chosen. In those cases, the fixed part of the operating cost of the facility is assumed to be 50 % of the values for SF and no MRS co-location, and no reduction is assumed in the package-dependent part of the cost estimate.

For Cs/Sr waste form in the fractionation cycle, storage costs are assumed to be 1/3 of the normal operating costs, for several reasons, namely the reduction in size and radioactivity with respect to SF canisters, the lower number of casks to be handled per year, and the elimination of canister receiving and inspection. The operating cost of the packaging facility when Cs/Sr canisters are being overpacked is assumed to be the regular cost for the minimum throughput option reduced by 50 % in both the fixed and the variable parts. The fixed part of the cost is reduced under the same assumptions that applied to the case of HLW/FHLW overpacking. In addition, the variable component of the operating cost is also reduced in this case because no Ti cladding is used, and it will presumably be easier to assemble the overpack. The consolidation line operating cost, regardless of where it takes place, is $9,100 per MTHM (54,55).

4. Cost of overpacks

The cost of the overpacks is always included in the packaging facility and is discounted according to the year they are used. Data from the Westinghouse designs have been used for both SF and HLW overpacks. The reference data (54,55) are given for designs for a repository in salt and tuff respectively. All overpacks include 2.5 mm of Ti on the outside surface and a carbon steel reinforcement of variable thickness. Disposal in tuff requires a thinner overpack, since the design pressure is the lowest. The highest design pressure corresponds to a repository in salt. For the purpose of this study, overpacks for a repository in granite or basalt are assumed to require the same overpack reinforcement thickness as for disposal in salt.

Different costs estimates for different sizes are given in the references 54,55, and they are listed below:

for a repository in tuff:

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Overpack I.D.= | 0.45 m; | Length = | 4.2 m; | Cost = | 19,402 | 1987 $ |
| " | 0.55 m; | " | 4.45 m; | " | 26,738 | " |
| " | 0.64 m; | " | 4.45 m; | " | 31,558 | " |
| " | 0.65 m; | " | 4.7 m; | " | 34,377 | " |
| " | 0.324 m; | " | 3.38 m; | " | 10,792 | " |
| " | 0.406 m; | " | 4.4 m; | " | 16,128 | " |

and for a repository in salt:

| | | | | | | |
|---|---|---|---|---|---|---|
| Overpack I.D.= | 0.43 m; | Length = | 4.2 m; | Cost = | 28,981 | 1987 $ |
| " | 0.49 m; | " | 4.45 m; | " | 31,952 | " |

| | | | | | | |
|---|---|---|---|---|---|---|
| " | 0.58 m; | " | 4.44 m; | " | 45,254 | " |
| " | 0.60 m; | " | 4.78 m; | " | 50,444 | " |
| " | 0.325 m; | " | 3.38 m; | " | 17,219 | " |
| " | 0.56 m; | " | 4.48 m; | " | 41,774 | " |

The length of the overpacks includes the top and bottom caps. Because the dimensions applicable in the present study are somewhat different, the overpack reference costs have been normalized to a basic length, 4.2 m for a SF canister and 4.32 m for a set of 3 HLW/FHLW canisters (one borehole). After the costs were normalized to the baseline length, the data were interpolated to calculate the cost of the overpacks for the diameters considered in the different scenarios. The final estimated costs are shown in Table C.2.

SF hardware, cladding hulls and Cs/Sr waste forms require a simpler overpacking, with no Ti-code. For hardware and hulls, data from reference 66 are used for an overpack of over 4 m, which would be equivalent to 3 1.3 m-long overpacks. In reference 7 the cost of the Cs/Sr canister overpack is given at $3,030 for a length of over 3 m, again corresponding to 3 of the canisters considered in the present study, of 1.2 m. This last source uses the same Westinghouse estimates for the FHLW overpacks. The overpack costs for these waste forms is also listed in table C.2.

## C. Repository Facilities and Disposal Costs

The cost of the repository facilities, excluding waste receiving, handling and packaging, and the cost of operations are divided into 11

TABLE C.2. Cost of the overpack for different canister types

| Waste type and size | Overpack ID (m) | Overpack length (m) | Cost (1987 $) Tuff | Other rocks |
|---|---|---|---|---|
| SF 3 a/c[a] | 0.34 | 4.2 | 13,800 | 22,480 |
| 6 a/c | 0.46 | 4.2 | 19,980 | 29,574 |
| 12 a/c | 0.62 | 4.2 | 29,200 | 45,800 |
| Reprocessed[b] | | | | |
| small | 0.32 | 4.32 | 13,790 | 22,000 |
| medium | 0.42 | 4.32 | 17,150 | 28,000 |
| large | 0.52 | 4.32 | 24,160 | 35,500 |
| Cladding hulls[b] and SF hardware | 0.60 | 4.2 | 4,000 | 4,000 |
| Cs/Sr[b] | 0.32 | 4.32 | 3,030 | 3,030 |

[a]a/c is number of assemblies per canister.

[b]For waste forms other than SF, the cost of the overpack corresponds to 3 canisters (one emplacement borehole) with the total length as given in the table.

different components. The following sections explain how the costs have been estimated for the different components.

## 1. Surface facilities capital cost

Depending on the repository design and the source, the costs of the surface facilities vary greatly, some estimates being as high as $1,400 M (73), for a repository capacity of 69,000 MTHM. In the cost analysis model, data from a standardization study (69) have been used for the surface facilities. The standardization study is based on 2 early repository designs in salt, NWTSR1 (National Waste Terminal

Storage Repository) and NWTSR2, and a reconciliation study (68) for the two designs. In this study a series of cost components are claimed to be non-site dependent and are applied to the two salt designs, and further extended to a design in granite and another in basalt, with different operation times. The site independent costs for the surface facilities are used as the reference costs for the repository facilities in the present cost analysis model. The baseline costs, escalated to 1987 dollars, with the maximum and minimum ranges are given in Table C.3, broken into the different components.

The range of the costs given in the table are in reasonable agreement with the total surface facility cost given in other cost analyses (70,71). The cost of the waste handling and packaging has been subtracted from the references for the comparison.

2. Ventilation structures capital and operating costs

An additional surface facility, not included in the previous section, but mentioned in some studies in particular, is the mine ventilation structure building. Reference 86 lists a cost of about $126 M for these structures, and a comparative study (74), lists a series of values for different cases, but with very small variation among them, so that an average value of $136 M has been calculated and used in the present cost analysis.

Extensive information on ventilation requirements does not exist for a radioactive waste repository, especially because the constraints applicable are not perfectly defined. Some design analyses have

TABLE C.3. Surface facilities capital cost

| Cost item | Cost in millions of 1987 dollars | | |
|---|---|---|---|
| | Baseline | Maximum | Minimum |
| Land rights | 22.43 | 33.64 | 22.43 |
| Land improvements | 36.39 | 36.39 | 36.39 |
| Off-site improvements | 14.76 | 14.76 | 3.79 |
| Administration Building | 13.39 | 13.39 | 13.39 |
| Maintenance building | 6.41 | 6.41 | 6.41 |
| Warehouse building | 4.19 | 4.19 | 4.19 |
| Sewage treatment | 0.57 | 0.57 | 0.57 |
| Substation building | 13.04 | 13.04 | 13.04 |
| Railroad Gatehouse | 1.02 | 1.02 | 1.02 |
| Firehouse | 0.74 | 0.74 | 0.74 |
| Generator plant | 17.64 | 35.29 | 17.64 |
| Development area plant | 1.51 | 1.51 | 1.51 |
| Ponds | 6.92 | 6.92 | 6.92 |
| Rock storage | 44.89 | 44.89 | 28.95 |
| Railroad receiving | 12.76 | 12.76 | 12.13 |
| Outside utilities | 16.02 | 16.02 | 16.02 |
| Water tower | 0.62 | 0.62 | 0.62 |
| Visitor center | 0.72 | 0.72 | 0.72 |
| TOTAL[a] | 214.0 | 269.0 | 187.0 |

[a]The total has been rounded off.

reported an estimated total cost of ventilation for the entire lifetime of the repository, typically on the order of $350-400 M (74,75).

In the present analysis, the ventilation cost is estimated proportional to the thermal power emplaced in the repository. Data from references (76,145) is used to obtain a ventilation unit cost. The ventilation cost is calculated in those references in the form of a value per 1000 canisters emplaced, each canister with a thermal output of 3.4 Kw at emplacement. Although it is mentioned that the ventilation requirements depend not only on the thermal power disposed, but also on the excavated volume, a lumped value will be calculated in the present study, for the excavated volumes are proportional to the power emplaced. The estimated costs include electric power, maintenance, labor requirements and materials.

Two different costs per 1000 canisters emplaced are given, one corresponding to mining operations and the second for emplacement operations, when the thermal sources are actually loaded. Based on the rated power per canister of 3.4 Kw a unit cost per Kw emplaced has been calculated, and escalated to 1987 dollars, for the two operations. For a number of years, disposal takes place at the same time as room and corridor excavation required for next year's waste disposal. The estimated ventilation cost of both mining and emplacement operations are applied to that period. After all the waste has been disposed, for a few years only backfilling operations are performed, and the ventilation cost applicable is that for emplacement (the heat sources are in place).

The costs estimates for both periods are \$614/year per Kw emplaced for the disposal period and \$409/year per Kw emplaced during the backfilling only period. The ventilation cost per year is calculated by multiplying the given unit costs per Kw by the number of Kw emplaced. Only the heat output of the waste disposed in rooms that have not been backfilled is included in the calculation of the annual cost. The total ventilation costs calculated for the lifetime of the repository are within a reasonable range of the global estimates given in some sources (74,75), if a comparable scenario is used.

3. Shaft construction costs

The general reference for estimating the cost of shaft contruction is a well documented study (59) written as part of the technical support for GEIS. The costs are estimated per unit of depth for different shaft diameters. The same diameters for the shafts are being used in the present study, so no correction or interpolation is made with data from the reference.

The costs are given in three components, sinking, lining, and hoisting, for salt, granite and basalt. Estimates for shaft construction in tuff are not given in the original source, but based on estimates for mining equipment for excavation in tuff (75), costs of sinking and hoisting are assumed to be equal to those in granite, lying between salt and basalt. Salt is expected to present more problems than any other rock for water control in the shafts, whereas granite and basalt do not require great lining expenses. Sinking shafts in tuff is likely to have some problems due to water control, especially if the repository is built below the water table. Therefore, the cost for lining in tuff is assumed at 50 % of the cost in salt.

The different costs are given in Table C.4, where distinction has been made between SF disposal (4 shafts required) and HLW/FHLW disposal (with 5 shafts). The costs compare well with other estimates of total shaft construction costs, after correction for depth (71,74,75).

TABLE C.4. Cost of shaft construction for different host rocks

| Item | Cost in thousands of 1987 dollars/m of depth | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | SPENT FUEL | | | | HLW / FHLW | | | |
| | Salt | Granite | Basalt | Tuff | Salt | Granite | Basalt | Tuff |
| Sinking | 145.9 | 93.1 | 134.4 | 93.1 | 171.5 | 111.5 | 163.6 | 111.5 |
| Lining | 97.6 | 4.3 | 8.4 | 48.8 | 114.8 | 5.4 | 10.5 | 57.4 |
| Hoisting | 74.7 | 67.0 | 63.5 | 67.0 | 79.7 | 72.5 | 68. | 72.5 |
| TOTAL | 318.2 | 164.4 | 206.3 | 208.9 | 366.0 | 189.4 | 242.2 | 241.4 |

4. Preoperations cost

This item includes the construction of the central pillar shaft area and the first set of tunnels in the mine development region, which are to delimit the first set of disposal panels and provide the ventilation paths. Also included in the preoperations expenses is the capital equipment cost of the mining and drilling machinery. Estimates for the first mine development area can be found in different sources (74,75,86), which are all within reasonable agreement. The preoperations cost will be dependent on the excavated rock, since in fact this preoperation reduces to the excavation and roof support of the central area. The cost estimates from reference 75 are used because this source uses the same mining costs utilized in the present study. The range for the preoperations ranges from about $34 M to $69

M, the highest estimate corresponding to basalt. The procedure used here has been to consider the cost of pre-mine development for basalt at $69 M. For the other rocks, the cost has been found by multiplying the estimate for basalt by the ratio of mining costs of basalt with respect to the other rocks. Using this procedure the cost estimates are:

| | |
|---|---|
| Salt | $ 36 M |
| Granite | $ 65 M |
| Tuff | $ 52 M |
| Basalt | $ 69 M |

The other component of the preoperations cost is the mining machinery, which has been estimated from reference (59), which is the same reference that will be used for mining cost estimates. The cost of the mining equipment for tuff has been assumed to be the same as for granite, which is in between salt and basalt. Adding the machinery cost, the final preoperations cost for the four different rocks is:

| | | |
|---|---|---|
| SALT | 90 | million 1987 dollars |
| GRANITE | 152 | million 1987 dollars |
| TUFF | 139 | million 1987 dollars |
| BASALT | 166 | million 1987 dollars |

5. Surface facilities operating costs

Although the capital cost of the surface facilities was obtained from the standardized repository costs study (69), the operational period of the repositories and the waste disposal rates are not similar to the scenarios of the present analysis. Other existing estimates cover too wide a range of values and designs as to be able to adapt their costs to the applicable scenarios. The approach that has been taken is to estimate the staffing necessary to operate the facilities. Information from two sources has been used (57,58) for determining the number of personnel. Again, because the scenarios contemplated in those sources do not coincide with the ones considered here, some changes have been made. Essentially, because of the relatively small number of packages to be handled per day, the evening shift has been reduced and the night shift has been eliminated, except for surveillance and security services. In the administration section, the required personnel has been assumed to be 1 for every 20 persons in the rest of the facilities. The underground personnel has been included in this calculation of administrative personnel, assuming a total of 300 persons in the underground facilities, conservatively. The estimated surface facilities staff involved in different operations, is shown in Table C.5. It must be recalled that receiving/packaging facilities are not included in this section.

The total number of personnel for the surface facilities is estimated at 303, and with and average salary of $35,000 per year, the annual costs would be $10.6 M. In addition, cost of materials and utilities necessary for the surface facility operations are considered to amount as much as the personnel expenses, which results in a total operating cost of $ 21.21 M for the surface facilities.

TABLE C.5. Estimated staff for surface facilities operations

| Operation | Personnel |
|---|---|
| Administration | 35 |
| Cafeteria | 14 |
| Materials | 20 |
| Maintenance | 20 |
| Safety | 32 |
| Security | 40 |
| Gates | 10 |
| Visitor Center | 3 |
| Warehouse | 8 |
| Fire Station | 30 |
| Storage Lab | 4 |
| Rock handling | 15 |
| Railyard | 4 |
| Training Center | 5 |
| Power plant | 12 |
| Medical services | 6 |
| Shaft operations | 45 |
| TOTAL | 303 |

## 6. Mining costs

The general source for estimating the mining costs is the study performed in support of GEIS (59). In this study the costs are estimated for excavation in salt, basalt and granite. The costs for excavation in tuff have been taken as half-way the excavation costs between salt and basalt, which is the approach followed in reference 75. The costs, expressed in 1987 dollars per $m^3$ of rock excavated, are seen in Table C.6. The mining equipment is not included in these estimates, for it has already been counted in the preoperations expenses. The hoisting charges from the original reference have been increased to account for deeper repository levels and have been homogenized.

TABLE C.6. Estimated mining costs for different host rocks

| Cost component | Cost in 1987 $\$/m^3$ Salt | Granite | Basalt | Tuff |
|---|---|---|---|---|
| Mining, haulage, power and support | 25.75 | 49.57 | 52.11 | 38.93 |
| Surface disposal | 2.35 | 2.35 | 2.35 | 2.35 |
| Hoisting | 1.72 | 1.72 | 1.72 | 1.72 |
| TOTAL | 29.82 | 53.64 | 56.18 | 43.0 |

7. Borehole drilling

The borehole drilling costs are function of the hole depth and diameter. The estimates in the references usually express the cost in dollars per unit depth. Correlations for the cost as a function of the diameter are given for salt, granite and basalt in reference (83). The estimates from this source for basalt and granite are in good agreement with values given in two other references, 33 and 75. For granite and basalt the estimates from 83 are used. The correlation for salt, however, seems to be off with respect to references (33 and 54 in particular), and these last references are used for salt. Since only the costs for certain diameters are given, a least-squares fit has been performed to the data. Because tuff is a rock mechanically more similar to salt, the same cost estimates obtained for salt are applied to borehole drilling in tuff.

The drilling costs per unit depth for the different rocks are given by the expressions:

GRANITE : 1987 \$/m of depth = 1904 $D^{1.31}$

BASALT : 1987 \$/m of depth = 2000 $D^{1.31}$

SALT and TUFF: 1987 \$/m of depth = 900 D

where D is the borehole diameter in m.

8. Emplacement operations

Several sources have divided the underground operation costs in such a way that the emplacement operations can be estimated as a unit operation. These estimates are normally high, considering that 60 manhours per borehole will be required (54,55,74), and some sources list an estimated cost close to \$9,000 per borehole when buffer, sleeve, and plug are included. Because in this analysis it is assumed that the emplacement operations will be performed by remote control, some savings can be expected.

A manpower requirement of 10 manhours is assumed to be necessary for each borehole. The hourly wages are estimated at \$40. The cost of the plug and sleeve that are installed in the borehole is estimated from data in 33 at \$1,720 per borehole. It is assumed here that this last cost is independent of the hole diameter, since the plug and sleeve materials are relatively cheap, and most of the cost accounts for manufacturing. Boreholes containing SF, HLW or FHLW canisters will have a bentonite buffer surrounding the overpack. Estimates of the cost of the bentonite material are taken from 55 and 53, although they have been reduced considerably. Both sources include a very high cost for inspection, chemical analysis, and quality assurance, of over $1,000 dollars per MT of buffer material. The buffer costs, as estimated in the present analysis are, assuming a 50-50 mixture of bentonite and crushed rock:

| | | |
|---|---|---|
| Material | 306 $/MT | |
| Pressing | 183 $/MT | |
| Emplacement | 160 $/MT | (4 manhours) |
| Inspection | 80 $/MT | (2 manhours) |

Using an average volume of bentonite buffer per borehole (not correcting for canister size), the buffer material for a SF borehole is estimated at $1,805 and for a HLW borehole (not as deep as a SF hole) at $1,020. Finally, adding up the costs of emplacement and bentonite, when applicable, the total emplacement costs are:

| | | |
|---|---|---|
| Spent Fuel | 4,385 | 1987 $ per borehole |
| HLW/FHLW | 3,600 | 1987 $ per borehole |
| Other waste | 2,580 | 1987 $ per borehole |

## 9. Backfilling, decommissioning and A-E costs

Backfilling costs are normally estimated as a percentage of the excavation costs. 25 % of the excavation costs is taken here as the baseline backfilling cost, in agreement with several references (54,55,74).

The decommissioning costs are calculated as a percentage of the total capital costs (surface facilities, ventilation structures and preoperations). An estimate of 15 % is used, as in references (33,69,70). In addition, the shaft sealing costs are also part of the decommissioning costs. Using data from 75 the shaft sealing costs are estimated at $ 1.33 M per meter of diameter for each shaft.

Architect-Engineering costs are also calculated as a percentage of the construction costs. In this case the cost of the surface facilities, ventilation structures, shaft construction and preoperations are included. The baseline percentage is 10 %.

# XIII. APPENDIX D. STRUCTURE OF THE ECONOMIC MODEL COMPUTER CODE

The computer code that was used for the calculation of costs is not listed here, but is filed in floppy disks. The structure of calling subroutines is given in this appendix, and is pictured in Figure D.1, in the form of a block diagram. The rock type, fuel cycle, canister size, MRS location, and the choice of the transportation option (leasing or buying the casks) is selected by the user in the form of Integer variables in the input file. The input file contains also variables to select the absolute cost of the repository surface facilities and preoperations. The operational costs, or the variations in the MRS facility costs are selected by factors that will multiply the default cost value, as listed in Chapter V and Appendix C. Finally, the optimization option, or a delayed start of diposal operations can be selected from the imput as well, along with a period of backfilling delay, in years.

The function performed by each subroutine is listed below:

MTFLOW - calculation the flow of waste by year.

TRONE - calculation the transportation costs to the MRS.

TRTWO - calculation the transportation costs from MRS to repository.

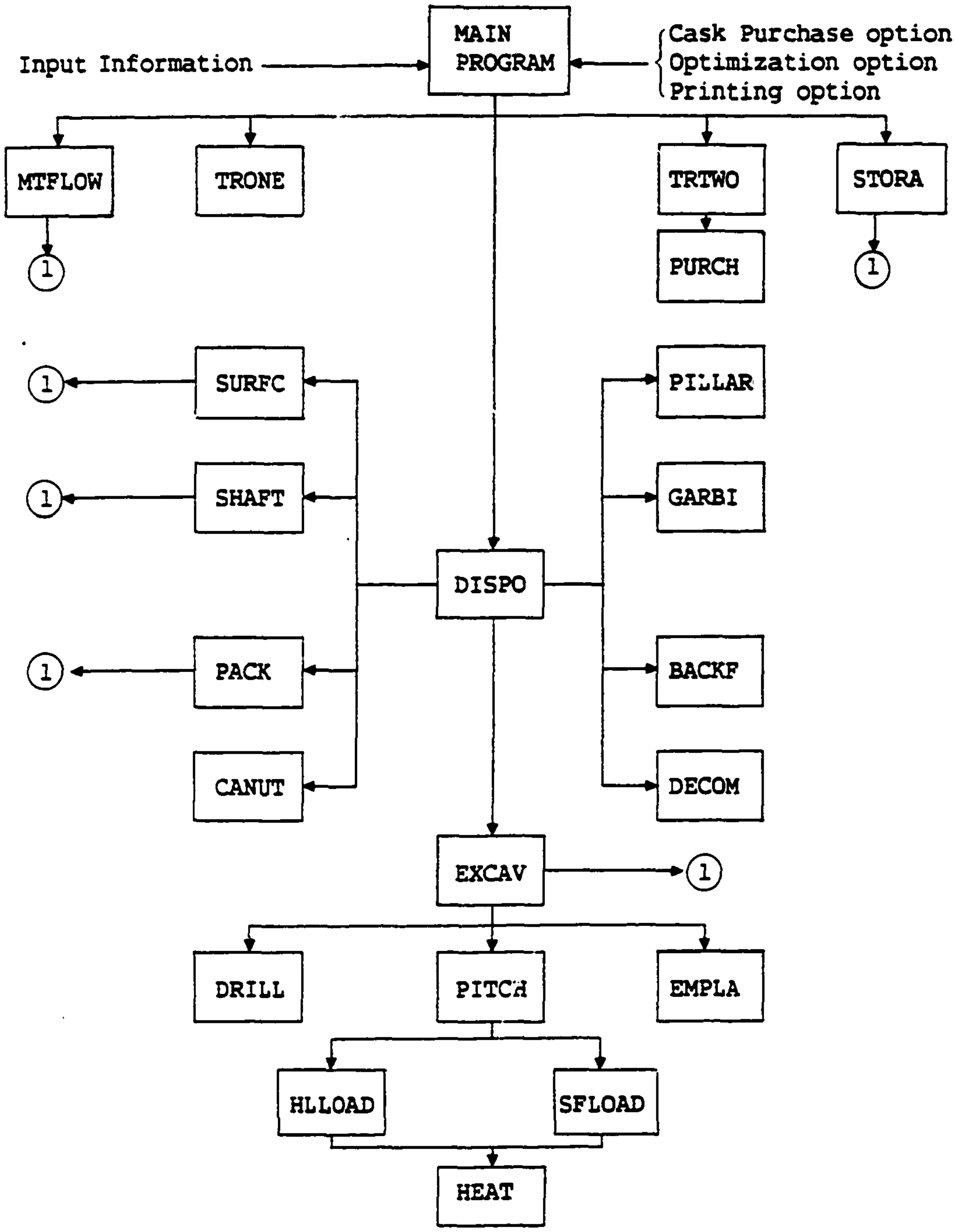
PURCH - optional evaluation of the cost of purchasing the transportation casks.

STORA - calculation storage costs.

DISPO - compilation of the components of the disposal costs.

SURFC - calculation of repository surface facility costs.

SHAFT - calculation of shaft construction costs.




(1)- Printout of operations/cost per year.

FIGURE D.1. Structure of the cost estimating program

PILLAR - calculation of preoperations costs.

PACK - calculation of packaging facility costs.

CANUT - calculation of overpack costs.

GARBI - calculation of ventilation costs.

BACKF - calculation of backfilling costs.

DECOM - calculation of decommissioning costs.

EXCAV - calculation of excavation requirements and costs.

DRILL - calculation of borehole drilling costs.

PITCH - estimation of minimum allowable canister pitch.

EMPLA - calculation of emplacement costs.

HLLOAD - evaluation of acceptable thermal loadings for HLW/FHLW.

SFLOAD - evaluation of acceptable thermal loadings for SF.

HEAT - decay heat calculations.

A sample of the input is also given below, and a brief explanation of each input variable is included. The input data is stored in a data file containing 8 lines with the following variables:

1. IR, IW, IC, ILM, IG, ICON, ICA
2. BUIL, VEN, FUN, PIL, CLEASE
3. DEPTH, CW, CH, RR, RW, RH, RL, BD
4. FASH, FAP1, FAP2, FPP, FDEC, FAE
5. FACEX, FABA, FASUP, FADRI
6. DR, FTL
7. FAST1, FAST2, FABUF
8. IOPT, IESC, KMRS, KDISP, KDB

Each input variable is briefly described below:

IR - Rock type: 1 for SALT, 2 for GRANITE, 3 for BASALT, 4 for shallow tuff, and 5 for deep tuff.

IW - Waste type: 1 for SF, 2 for HLW, and 3 for FHLW.

IC - Canister type: 1 corresponds to SF with 3 a/c, 2 to SF with 6 a/c, 3 to SF with 12 a/c, 4 to HLW/FHLW-3010, 5 to HLW/FHLW-3015, 6 to HLW/FHLW-3020, 7 to HLW/FHLW-4010, 8 to HLW/FHLW-4015, 9 to HLW/FHLW-4020, 10 to HLW/FHLW-5010, 11 to HLW/FHLW-5015, and 12 to HLW/FHLW-5020.

ILM - MRS location: 1 if co-located with repository and 2 if located in Tennessee.

IG - Air gap: 1 if air gap exists and 0 if it is not considered.

ICON - Consolidation location: 1 at disposal site and 2 at MRS.

ICA - Purchasing option for transportation casks: 0 if casks are leased and 1 if they are purchased.

BUIL - Cost in dollars of repository surface facilities.

VEN - Cost in dollars of ventilation structures.

FUN - Annual operating cost of repository surface facilities.

PIL - Cost in dollars of preoperations.

CLEASE - Transportation cask leasing fee (in dollars per day) if any.

DEPTH - Repository depth, in m.

CW - Corridor width in m.

CH - Corridor height in m.

RR - Room-to-room distance in m.

RW - Disposal room width in m.

RH - Disposal room height in m.

RL - Disposal room length in m.

BD - Borehole diameter in m.

FASH - Shaft construction cost factor; baseline = 1.0.

FAP1 - Packaging facility capital cost factor; baseline = 1.0.

FAP2 - Packaging facility operating cost factor; baseline = 1.0.

FPP - Overpack cost factor; baseline = 1.0.

FDEC - Decommissioning cost factor; baseline = 0.15.

FAE - A-E cost factor; baseline = 0.10.

FACEX - Emplacement cost factor; baseline = 1.0.

FABA - Backfilling cost factor; baseline = 0.20.

FASUP - Excavation cost factor; baseline = 1.0.

FADRI - Drilling cost factor; baseline = 1.0.

DR - Discount rate.

FTL - Thermal loading safety factor.

FAST1 - Storage facility capital cost factor; baseline = 1.0.

FAST2 - Storage facility operating cost factor; baseline = 1.0.

FABUF - Ventilation cost factor; baseline = 1.0.

IOPT - Optimization option: 0 for fixed schedules and 1 for optimization.

IESC - Printout option - 0 for summary printout and 1 for detailed by year printout.

KMRS - MRS start up year, 1998.

KDISP - Repository start up year; baseline = 2003.

KDB - Delay backfilling; baseline = 5 years.